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Proceedings of Contractors' Meeting, Technical and Economic Analysis, U. S. Department of Energy Office of Advanced Conservation Technologies

April 21-22, 1981
Chicago, Illinois

Storage is the Central Link
of the Energy Chain

prepared by
ARGONNE NATIONAL LABORATORY
Energy and Environmental Systems Division

for
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PROCEEDINGS OF CONTRACTORS' MEETING, TECHNICAL AND ECONOMIC ANALYSIS, U.S. DOE OFFICE OF ADVANCED CONSERVATION TECHNOLOGIES*

April 21-22, 1981
Chicago, Illinois

Hosted by Argonne National Laboratory

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prepared for

U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Conservation and Renewable Energy
Office of Energy Systems Research

*Now the Office of Energy Systems Research.

NOTICE

The papers in these proceedings appear as received from the Department of Energy contractors who participated in the information exchange meeting, with only minor editorial corrections.

CONTENTS

FOREWORD

A Contractors' Information Exchange Meeting for the Technical and Economic Analysis (TEA) subprogram of the Office of Advanced Conservation Technologies (ACT)*, U.S. Department of Energy was held in Chicago on April 21-22, 1981. The direct purpose of the meeting was to provide a forum for the discussion of progress on projects supported by the TEA subprogram. Specific objectives were to:

- Provide for technical information exchange and peer review of activities and research programs of the Technical and Economic Analysis subprogram.

- Develop a common understanding of the TEA subprogram mission, objectives, and program activities.

- Disseminate new information about the economics, availability, and technical promise of advanced conservation technologies.

- Provide feedback of information for the advanced conservation technologies R&D program planning and management.

Opening remarks were delivered by Dr. John J. Roberts, Argonne Associate Laboratory Director for Energy and Environmental Technology, who welcomed the meeting participants and discussed the importance of storage in the national energy economy. John J. Brogan, Director, Office of Energy Systems Research (ESR), then presented an overview of the DOE/ESR program. Veronika A. Rabl, Program Manager, Technical and Economic Analysis, described the ESR/TEA subprogram. The progress reports delivered by the contractors are presented in this proceedings.

Special thanks are extended to the chairpersons of the sessions who kept the discussions focused and the program running smoothly -- Kenell G. Touryan, Solar Energy Research Institute; Dean W. Boyd, Decision Focus, Inc.; Robert L. Mauro, Electric Power Research Institute; and Robert F. McAlevy III, Stevens Institute of Technology. We would also like to acknowledge the outstanding keynote presentation by Dr. Theodore Eck, Chief Economist, Standard Oil of Indiana. Finally, we thank Eileen Schmitz, Conference and Publication Services, and her staff for their help in organizing the conference.

Joseph G. Asbury

Joseph G. Asbury

Robert Swaroop

Robert B. Swaroop

*Recently renamed Office of Energy Systems Research

OPENING SESSION

ADVANCED CONSERVATION TECHNOLOGIES
PROGRAM SUMMARY

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The Office of Advanced Conservation Technologies (ACT)*, U.S. Department of Energy, is responsible for a broad-based, long-term, high-rise, high-payoff research program designed to increase fuel-use efficiencies, increase the use of renewable but intermittent energy sources to provide continuous service, increase effectiveness of baseload electric power generation and distribution systems by eliminating or reducing the need for new peaking equipment, and increase efficiency and reliability of the national electrical system while reducing transmission and distribution losses. The cross-cutting research program is being developed to substitute coal, nuclear, and solar energy for Energy Storage, Physical and Chemical Energy Storage, Energy Conversion and Utilization Technologies, and Electric Energy Systems.

Electrochemical Energy Storage Division

The Electrochemical Energy Storage Division is responsible for directing research programs on cells and modules for battery systems for transportation, utility load-leveling, solar, and other technologies. The division also manages programs in electrochemical processes to increase industrial energy efficiency and in conservation of scarce fossil fuels and other resources. Specific responsibilities include determining the feasibility, practicability, and ultimate application of electrochemical storage systems technology, providing program definition and support to promising advanced electrochemical concepts, technologies and systems, and developing acceptable electrochemical storage systems for all energy-using sectors.

Physical and Chemical Energy Storage Division

Work within the Physical and Chemical Energy Storage Division consists of applied research, exploratory development, and technology base activities in the areas of thermal, chemical, mechanical, underground, and magnetic energy storage systems. Emphasis is placed on effecting energy savings or substitution through the development of systems that store electricity, industrial waste heat, and solar energy. The energy storage devices under development should find uses in the transportation, building, utility, and industrial sectors of the economy.

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Energy Conversion and Utilization Technologies Division

The Energy Conversion and Utilization Technologies Division is responsible for development of an improved technology base for energy conversion and utilization systems and for development of advanced concepts for increased productivity and fuel-switching capability. The division achieves these goals through a program of generic and applied research and exploratory development managed through DOE field offices and conducted by universities, private-sector laboratories, and government laboratories. The program is planned, conducted and evaluated in cooperation with technology-using industries to assure prompt dissemination and utilization of advanced design and development techniques that constitute the principal outputs from the program.

Electric Energy Systems Division

The Program of the Electric Energy Systems Division is designed to help ensure that the nation's electric energy system is capable of meeting future demands in a reliable manner with the lowest practical energy losses. Toward this end, the division supports research to improve the efficiency of the electrical energy system and to enhance the efficiency of energy generation, transmission, and distribution. The division is charged with developing technical solutions for high-capacity transmission corridor siting problems and analyzing systems losses and equipment to improve the efficiency of the electrical network.

TECHNICAL AND ECONOMIC ANALYSIS SUBPROGRAM OVERVIEW

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The mission of the Technical and Economic Analysis (TEA) subprogram of the Office of Advanced Conservation Technologies (ACT)*, U.S. Department of Energy, is to provide information and decision criteria needed to set and continuously evaluate energy storage research and development program objectives. The efforts of the Technical and Economic Analysis subprogram are concentrated into three main areas: applications analysis, R&D program evaluation, and information management.

Applications Analysis

Applications analysis quantifies factors that help determine the R&D requirements of storage technologies as well as the suitability of their applications. The program identifies customers and needs for energy storage and provides information concerning the expected benefits, costs, and performance requirements for new technologies. Applications analysis information also provides the basis on which to set and evaluate priorities for competing technologies in specific applications. Impact assessments of energy storage technologies identify energy and cost savings, environmental, health and safety effects, and institutional barriers and incentives.

Storage applications span the full spectrum of end-use sectors and interface with a number of other technologies, imposing, in general, a diverse set of requirements. This diversity is reflected in the projects discussed in this meeting.

R&D Evaluation

R&D evaluation activities assist in developing criteria necessary to establish R&D program requirements. Information from the applications analyses is used to evaluate competing technologies and research projects, compute the corresponding risks, costs, and benefits, and recommend Federal R&D resource allocations.

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Information Management

The key to effective R&D program decision-making is the development and availability of accurate and timely information. To this end, the TEA subprogram is developing technology and bibliographic data bases to provide information transfer to both public and private sectors. Within this area, the Lawrence Livermore National Laboratory has developed a highly interactive, self-guided computerized information system known as the Technology Information System (TIS). Current efforts are aimed at refining and updating the existing TIS system.

SESSION I:
STORAGE FOR SOLAR APPLICATIONS

ADVANCED ENERGY STORAGE SYSTEMS

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ABSTRACT

The Committee on Advanced Energy Storage Systems of the National Research Council has now completed six years of existence, and is now awaiting a contract extension for another three years of activities in support of the Technical and Economic Analysis group. During FYs '80 and '81 the Committee issued two reports: Hydrogen as a Fuel, and Energy Storage for Solar Applications. Two more studies are currently underway. One is looking at the technical prospects for storage driven vehicles other than those powered with secondary batteries, and their implications for R&D programs. The other is studying how analyses can better serve energy storage R&D decision making, with particular emphasis on the interface between strategic and budget planning. The Committee is now considering future successor studies, but has not as yet made final decisions.

BACKGROUND

The Committee was organized in 1975 by the National Research Council in response to a request from the AEC/ERDA. The Committee was broadly charged with (1) developing criteria that should be applied in the selection of major R&D development or demonstration projects if the project results are to have a high probability of commercial use, (2) developing criteria that should be applied to determine the categories of R&D to be funded by government rather than by industry, and (3) developing broad priority considerations in selecting program content.

During the initial one-year contract period, the Committee organized six study panels to look at different areas of storage applications: electric utilities, residential/commercial, industrial, transportation, solar-electric, and fusion reactor systems. A report, Criteria for Energy Storage R&D, was issued in the summer of 1976.

During the course of the initial contract period, a decision was made to extend the life of the Committee for another 2 1/2 years, through December 1978, so that several specific storage topics that had emerged from the general study could be addressed. Three new study panels were organized in this period.

A Transportation Panel examined the implicit battery development schedules that were effectively mandated by the Electric and Hybrid Vehicle RD&D Act of 1976 and compared them with characteristic development schedules determined from experience. The resultant report, Development Schedules for Vehicle Energy Storage Systems, issued in September 1977, showed why additional lead time would be required before advanced electric vehicles could be demonstrated in conformity with the purposes of the Act.

The Transportation Panel continued its studies with an examination of the programmatic fit between the advanced battery development plans of STOR and the vehicle demonstration plans of TEC for electric vehicles. A letter report to the Director, STOR, was issued in December 1978 which identified potential gaps between the two program plans in the areas of in-vehicle battery testing, the provision of adequate battery production facilities, and the achievement of postulated battery cost reductions.

In the 1977-78 time period two additional study panels were organized to study topics related to hydrogen production and storage and to the storage R&D needs associated with solar energy installations. The work of these panels was not completed until FY '80-'81 and will be reported in the next Section.

In January 1979 the Committee's life was extended for another two years, through December 1980. Two additional study topics were adopted and two new study panels were created during this period. Their work is described in the Section on Current Activities.

Another 3-year extension of the Committee's life is currently being processed. Some of the possible directions of Committee studies are discussed in the Section on Future Plans.

REPORTS IN FY '80-'81

Hydrogen as a Fuel

There is no single point of responsibility for R&D on hydrogen systems within the DOE. In addition to its responsibility for hydrogen storage system R&D, the Energy Storage Systems Division has also been assigned responsibility for R&D on production of hydrogen from non-carbon sources. At the request of the Division, the Committee organized a Hydrogen Panel to determine suitable criteria for establishing the pace, timing, and technical content of appropriate R&D programs. During the early course of its deliberations, the panel concluded that the criteria for R&D programs in support of hydrogen production, transport, and storage could not be developed without a concurrent examination of the status and problems of potential hydrogen uses. This, therefore, became a major part of the study.

In its report, Hydrogen as a Fuel, issued in November 1979, the panel concluded that anticipated growths in hydrogen consumption as a major chemical intermediate, as a reducing gas, and for a variety of special applications can probably be accommodated by normal market expansions of present manufacturing and distribution capabilities, and that new capabilities will only be needed if sizeable markets develop for hydrogen as a fuel. The study, therefore, examined possible hydrogen fuel market areas in considerable depth. In particular, the report examined hydrogen as a heating fuel, as an automotive fuel, and as an aircraft fuel. The report also examined the status and problems of hydrogen transport and storage systems and of fuel cells which may be an integral part of future hydrogen utilization systems.

It was concluded that while hydrogen has a future potential as a heating fuel, natural or synthetic hydrocarbons will remain the preferred energy carriers in competition with electricity as long as fossil fuel sources are economically available. If it becomes necessary to shift fuel dependence away from fossil sources, then hydrogen derived from non-fossil (nuclear and solar) energy sources might become competitive to electricity generated from the same sources because of more favorable transmission and distribution characteristics, end uses which lend themselves to gaseous fuels, and probably cheaper storage techniques.

The potentially largest hydrogen fuel market could come in the automotive field if a market for non-gasoline vehicles is established. Low cost, highly efficient hydrogen/air fuel cells, which are theoretically achievable, might compete successfully with advanced secondary batteries as automobile power sources under such circumstances.

Future civil transport aircraft may also create a hydrogen fuel market. In particular, if the development of a long-range supersonic transport were to be adopted as a national goal, serious consideration should be given to the use of hydrogen as the SST fuel.

The report considers that the cost differentials which presently inhibit the use of hydrogen as a fuel will probably continue to exist in the foreseeable future. If a fuel market for hydrogen is to be developed, it is probable that the hydrogen would have to be derived from either non-carbon sources or as an end product of a coal/synthetic-fuel chain. Costs of either type of hydrogen will be higher than the costs of synthetic hydrocarbons that are suitable for fuels. As a consequence, it is by no means certain that a widespread market for hydrogen as a fuel will materialize until it is forced by hydrocarbon limitations.

In spite of reservations about the timing and rate of impact of hydrogen as a fuel, the report concluded that there is a need for a well-conceived R&D program to study some of the basic problems that may constrain hydrogen's future entrance into the national fuel economy. Specifically, the report recommended that:

- Basic exploratory research should be pursued on innovative concepts related to the production, transmission, distribution, storage, or use of hydrogen even if near-term market needs cannot be identified.

- The federal program should be complete enough to provide a data base that will enable sound future evaluations and decisions to be made about more costly development and demonstration programs.

- Such large-scale development and demonstration decisions should be deferred until a market need is identified and it is established that the private sector will not undertake the necessary effort.

- Particular research attention should be given to the understanding and resolution of potential safety problems associated with the introduction of all phases of the hydrogen production-use chain into the energy complex.

The report suggested that the U.S. R&D program on hydrogen should continue to recognize the greater potential need for hydrogen fuels in other nations and the possibility that other nations may attain a position of research leadership. The U.S. program should be in areas clearly applicable to domestic interests, and should not attempt to completely duplicate foreign efforts.

Energy Storage for Solar Applications

Most forms of solar energy are intermittent in nature and, therefore, cannot be relied upon to supply energy at rates which coincide with typical energy consumption needs. Among the techniques for achieving the ultimately necessary supply/load match are energy storage systems. In 1978 the Committee created a Solar Energy Panel to study the nature of the interface between solar installations and energy storage systems in order to determine the need, if any, for new or expanded storage R&D programs to ensure that the future utilization of solar energy would not be hindered by inadequate storage know-how. The panel's findings are contained in a report, Energy Storage for Solar Applications, which was issued in January 1981.

The panel studied three important solar conversion modes: low-temperature thermal systems (for water heating and space conditioning); high-temperature thermal systems (for electricity generation or industrial process heat supply); and direct photovoltaic and wind energy systems (for electricity generation). Other solar applications in which the use of storage is not primarily to improve the match between energy demand and solar-derived energy supply were not examined.

As long as solar energy only supplies a small fraction of the energy in an energy system--whether a building, an industrial process, or a utility--specific backup measures to correct energy demand/solar-supply mismatches are not normally required. As the fraction of energy supplied by the solar source is increased, backup delivery systems are increasingly required. The main backup system options include fuels consumed on site, electricity supplied from a grid, and storage of the solar energy. The solar energy fraction beyond which backup is essential and the choice of backup systems are complicated considerations for which readily usable analytic tools and data appear to be lacking.

If energy storage is the preferred backup system, it can:

- Store solar energy at or near the conversion site ("dedicated" storage), or

- Store either solar energy or energy made available through an electricity grid ("system" storage).

These storage systems serve different functions in conjunction with solar conversion systems and thus must meet different technical and economic requirements.

- Dedicated storage will be necessary when the solar energy is used in stand-alone energy delivery systems.

- System storage will be appropriate when the solar energy supplies appreciable amounts of electric power in applications that are integrated with an electricity grid.

[There is a wholly different kind of storage that is important for some solar installations. This is internal system storage that is provided to permit the system to maintain uniform operating conditions in the event of either fluctuating solar inputs or fluctuating loads. This "buffer" storage is only used as needed to assure solar system operability and reliability; it should be treated from a different viewpoint than energy backup storage. The buffer storage must be engineered into a specific solar conversion system and be fully integrated with it. It appears that insufficient attention has been paid to the acquisition of the necessary design information.]

The study concluded that only application-specific system level analyses can determine whether solar energy storage or fuel storage provides the most appropriate backup, or whether dedicated or system storage is preferable. Whether storage systems need to be available at all for use with solar installations, what types of storage should be used when needed, and at what future time such storage will be needed cannot be deduced with confidence solely from technical judgements. Societal and institutional preferences will influence the rate of adoption of solar systems and the consequent need for storage systems.

The panel developed a number of specific conclusions and recommendations on the storage of solar derived energy and the kind of storage R&D that is indicated. In the case of low-temperature thermal systems, the panel considered costs, materials, availabilities, and site and structural limitations to be the major obstacles to the widespread public acceptance and use of such solar applications, rather than inadequate storage technologies. The panel felt that the private sector is very capable of developing and improving the small scale water or rock storage systems needed for individual residential or commercial installations, but felt that the DOE should expand R&D on community level, seasonal storage system concepts. The DOE should also remain alert to any highly innovative new storage concepts that might warrant R&D support.

In the case of high-temperature thermal solar systems, the panel felt that the present DOE programs on utility storage systems are well suited to any short term backup needs of thermal-electric systems, and that realistic lead times and priorities for the deployment of such systems should be analyzed before other storage backup programs are undertaken. The adequacy of buffer storage systems for thermal-electric installations does need examination. Specific requirements for industrial process heat systems need to be examined by the DOE to make certain that storage systems will not limit important solar installations, and any actual R&D should be closely identified with specific applications.

For grid-connected direct mechanical/electric solar systems, it was felt that the system level storage now being developed for utilities would suffice for any storage needs. Additional research is needed for storage with systems to be deployed for stand-alone uses, which may constitute a major part of the solar-electric market in developing countries.

CURRENT ACTIVITIES

Storage Vehicles

The several studies on transportation related storage problems repeatedly indicated relatively low daily range capabilities for the storage systems selected for development and demonstration in the DOE program. While recognizing that substantial specialty markets might exist for such vehicles, the Committee felt that a much larger market with a much greater fuels saving potential might exist in the future for storage vehicles having performance characteristics that are more competitive with those of conventional passenger automobiles. Accordingly, in late 1979 the Committee created a Storage Vehicles Panel to examine the automotive potential of storage systems other than secondary batteries, to compare those with the corresponding potential of secondary battery systems, and to make appropriate recommendations regarding desirable R&D programs.

The panel has investigated primary batteries (aluminum/air), fuel cells, and flywheels in terms of both their stand-alone and hybrid potentials. In addition, it has reviewed the status and problems of the principal secondary batteries under DOE development. A first draft of the panelists' reactions to the material that they have covered is now being prepared. It is hoped that a final draft can be ready for review this summer.

Study Standards

In its earlier studies, the Committee and its Panels identified the complexities of properly analyzing storage concepts in the context of total energy systems and in making the proper comparisons among storage concepts and between storage and alternate load management techniques. As a consequence, the Committee organized a Study Standards Panel in the fall of 1979 to consider possible recommendations on guidelines for analyses in support of energy storage R&D decision making.

Early in its deliberations, this Panel concluded that there was a probable need for a strong tie between long-range strategic planning and short-range program planning. A two-day workshop was held at the NAS Woods Hole Study Center in July 1980 for a discussion of the strategic planning approaches used by non-governmental establishments engaged in major R&D (G.E., DuPont, EPRI, and GRI) and the applicability of their approaches to planning in the DOE. A first draft of a report on the Panel's findings is in preparation.

FUTURE PLANS

The Committee is currently awaiting the formal extension of its contract with the DOE. Pending that extension, there can be no substantive activities that would involve Committee travel or the accrual of other major support expenses. This, coupled with the program uncertainties introduced by the revised '81-'82 budget plans of the new administration, has prevented the Committee from adopting a specific study plan to succeed the two on-going activities.

The currently most likely study would involve the identification of the basic research needs of the various storage technology areas and the interface of such work with on-going or planned undirected research in the DOE. The Storage Vehicles Panel has tentatively identified such needs in the battery area; it is presently uncertain whether there are similar needs in other storage areas.

The Committee is also considering the needs, if any, for a study of the impact of changing technical and economic conditions on the long-term storage needs of the electric utility industry, and the effects on storage R&D requirements.

ASSESSMENTS OF ENERGY STORAGE FOR SOLAR APPLICATIONS

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ABSTRACT

An overview of the first three phases of the Solar Applications Analysis for Energy Storage study performed for the Office of Advanced Conservation Technologies of the Department of Energy is presented. Phase 1 surveyed solar energy applications, Phase 2 developed a uniform methodology for assessments, and Phase 3 summarized prior applicable storage assessments. Three referenced reports thoroughly cover each of the phases and are available from the authors.

INTRODUCTION

The Aerospace Corporation is coordinating a multilaboratory study for the Office of Advanced Conservation Technologies, the objective of which is to assess the technical and economic viability of energy storage in near-term solar energy applications. Near-term applications are those having the potential for significant market penetration by the year 2000. The results of the study will assist the Department of Energy, Office of Advanced Conservation Technologies, in formulating its research programs to meet national needs. The study is being accomplished in five phases:

Phase 1: A survey of solar energy applications to determine potential roles for energy storage systems and to select application areas for emphasis.

Phase 2: The development of a uniform methodology for assessments to ensure a valid basis for comparing energy storage systems for a particular application.

Phase 3: The preparation of a summary of prior storage assessments applicable to the energy storage applications defined in Phase 1.

Phase 4: The evaluation of existing assessments, summarized in Phase 3, and the conduct of additional assessments as required, based on the results of Phase 3 (to be accomplished by the Department of Energy national laboratories and the Solar Energy Research Institute).

Phase 5: The preparation of recommendations for future solar energy storage research based on the results of the assessments conducted in Phase 4.

This paper discusses the results of the first three phases of the study. The status of the fourth phase will be discussed in succeeding papers. The fifth phase is scheduled for completion in the June/July 1981 time period.

SELECTED APPLICATIONS

The survey of solar energy applications to determine potential roles for associated energy storage systems resulted in the selection of five applications as candidates for assessment. The five applications originally* selected and the organizations performing the analysis are as follows:

- Agricultural and industrial process heat -- active solar thermal energy source - Solar Energy Research Institute
- Residential and commercial space heating/cooling and hot water -- active solar thermal energy source - Solar Energy Research Institute
- Electricity for central/community applications -- wind energy source - Sandia National Laboratories/Albuquerque
- Electricity for central/community applications -- photovoltaic energy source - Sandia National Laboratories/Albuquerque
- Residential, commerical, and light industry space heating and cooling -- passive solar thermal energy source - Brookhaven National Laboratory

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* The two central/community applications were dropped because previous assessments had shown that storage dedicated to the energy source was not the best way to proceed. These were replaced by electricity for building services, whose energy source is wind or photovoltaics.

The selection process was accomplished in three steps: (1) matrix evaluation, (2) review by the Office of Advanced Conservation Technologies, and (3) comparison with the Domestic Policy Review of Solar Energy. The first step involved the development of a set of matrices of potential solar energy applications/energy storage technologies. These matrices were developed to screen all possible combinations of solar and storage technologies with the intent of identifying those combinations that could possibly satisfy near-term national energy goals. This implies either state-of-the-art technology or technology that could be developed by 1985. The applications were then evaluated according to their potential for meeting the goals, which resulted in 26 solar/storage applications with significant potential.

The second step consisted of obtaining the opinions of the Office of Advanced Conservation Technologies technical staff regarding which solar applications would require further analysis from a storage point of view. Eight of these 26 applications were judged by the staff to have significant potential.

The third step was a review of the Domestic Policy Review of Solar Energy and its interpretation as provided in the Draft DOE Policy, Programming and Fiscal Guidance, FY 1982-1986, January 30, 1980. In comparing the Domestic Policy Review high-potential solar applications with the staff recommendations, six applications were seen to be common to both. From these, four applications were chosen for further analysis in FY 1981. Solar thermal energy for space heating of buildings was divided into passive and active systems, which brought the number of applications for study in FY 1981 to five, as defined previously. The details of the Phase 1 study are presented in "Selection Rationale for High-Value Solar/Energy Storage Applications."[1]

UNIFORM ASSESSMENT METHODOLOGY

The objective of Phase 2 was to develop a uniform methodology to ensure that the assessments done in Phase 4 are completed on a common basis. This has been accomplished by delineating both the governing assumptions and the figures of merit to be used in the assessments. The major governing assumptions include the specification of the regional data; the energy forecast scenarios; and the standards for cost estimating, including economic and financial calibration values. The details of this methodology are presented in "Uniform Assessment Methodology for Energy Storage Applications."[2]

System Methodology

The overall system methodology flow, as indicated in Figure 1, basically optimizes a system first without, then with, energy storage. The assessment is initiated with the selection of the solar application and the identification of the candidate energy conversion technologies and the associated storage systems to be considered for that application. The analysis is performed for one or more of several different energy and economic scenarios and one or more Typical Meteorological Year cities.

The energy and economic scenario chosen provides input values for a range of energy and economic parameters. The choice of a particular scenario implies acceptance of the driving assumptions of that scenario. Specifically, the use of a high world oil price (the high scenario) carries with it assumptions concerning the prices of alternative fuels, the availability of alternative fuels, and the projected level of economic activity over the next 15 years. Included in the scenarios are projections for the price of electricity, gas, and other fuels used to generate electricity and assumptions about the particular time-of-day pricing structure, the prevailing discount rate, the financial structure for a homeowner application, the prevailing property tax rate, the income tax rate, salvage values, and other nonregional components of the analysis. A number of highly regionalized values are also selected, including regional fuel prices; system-specific cost values, such as capital cost per kilowatt; operation and maintenance costs; and other elements that would be used in defining the stream of life-cycle costs. All of the aforementioned parameters are used to estimate the benefits and costs of the application on a with- and a without-storage basis for both stand-alone and grid-connected applications. The various markets that might conceivably install the device (homeowners, regulated utilities, unregulated industry, or government) all have different figures of merit by which they would assess the value of including storage capacity in the application.

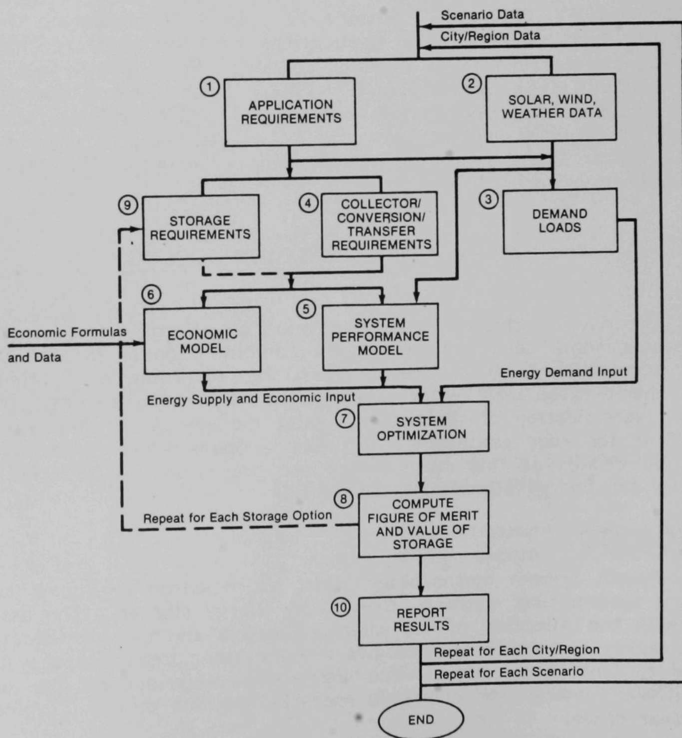

Figure 1. System Flow

Standardization of Regional Data

The selection of standardized solar, wind, and weather data is based on the examination of three candidate data bases: the Test Reference Year, the Westinghouse-SOLMET year, and the Typical Meteorological Year. Each of these data bases was examined in some detail, resulting in the selection of the Typical Meteorological Year data for use in this study. It not only considers radiation, but also wind, temperature, and humidity.

Energy Forecast Scenarios

The Energy Information Administration, a component of the Department of Energy, is responsible for processing and publishing data on energy reserves, production, demand, consumption, and the financial status of energy-producing companies. Both the Federal Energy Administration Act of 1974 and the Energy Conservation and Production Act of 1975 require that the Administration prepare an annual forecast of energy production and consumption in the short-, mid-, and long-term periods. These forecasts are published as part of the Administration's annual report to Congress. The Administration energy projections should be incorporated in assessments of the value of solar energy storage because (1) they are the official Department of Energy projections, (2) they include a broad range of scenarios that are broadly accepted, and (3) the energy equilibrium model used is multiregional.

Economic and Financial Calibration Values

The economic and financial calibration values are generally given as ranges of parameters, including one calibration value that will be used in future assessments to calibrate results from assessment to assessment. These values and ranges are presented in Section 5 of the methodology report.[2]

Figures of Merit

A single standard measure of system performance is required as a guide to the optimization of the system design. Many technical measures of performance are available; however, their optimization criteria are usually mutually exclusive. Therefore, an economic figure of merit is used as the objective function for optimization in this analysis. The economic figure is a measure of the relative value of the system from the perspective of the potential purchaser. It includes an implicit weighting of the technical performance criteria as they affect the value.

The energy systems are evaluated from the perspective of four application sectors:

- Homeowners
- Commercial and industrial firms
- Privately owned, regulated utility firms
- Government

The system optimization is based on a single figure of merit. Further analysis of the system, however, may require other figures of merit representing particular aspects of the system in each application. This is analogous to the situation that will be faced by the manufacturers of these systems. They will have to standardize the systems according to some general market guidelines in order to realize the economies of large-scale production. Having done that, they may promote the systems in different market segments according to the features that are most desirable to those segments.

The figures of merit developed in this analysis differ among the application sectors. These figures include those most commonly used in energy system studies, but the list is not exhaustive. Some studies may develop additional figures of merit, although the figures described in this analysis should be common to all future studies to ensure comparability of the results. The first named figure of merit was used in the optimization procedure, and the remaining were calculated based on that optimized system.

Application Sector	Figures of Merit
Homeowners	Net Present Value Benefit/Cost Ratio Initial Cash Outlay Payback Period
Industry	Net Present Value Benefit/Cost Ratio Internal Rate of Return Payback Period
Utilities	Net Present Value Benefit/Cost Ratio
Government	Net National Economic Benefit

The following is a typical calculation of a figure of merit equation for homeowner life cycle cost.

$$LCC = DP - ITC_{PV} - SV_{PV} + RC_{PV} + LP_{PV} + FP_{PV} - ES_{PV} + OM_{PV} + PT_{PV}$$

VARIABLE	DESCRIPTION
LCC	Life Cycle Cost
DP	Down Payment
ITC_{PV}	Present Value of the Initial Energy Investment Tax Credit
SV_{PV}	Present Value of the Expected Salvage Value
RC_{PV}	Present Value of Future Component Replacement Costs
LP_{PV}	Present Value of Loan Payments
FP_{PV}	Present Value of Fuel and Electricity Purchases
ES_{PV}	Present Value of Electricity Sold Back to Utility
OM_{PV}	Present Value of Operations and Maintenance Expenses
PT_{PV}	Present Value of Property Taxes

This analysis does not treat the Federal Government as a separate application sector for which solar energy or storage systems will be simulated and optimized. Rather, the Government assesses these systems from a national resource use perspective by examining the simulated actions of the private decisionmakers in the other sectors. For this purpose, a net national economic benefit (NNEB) equation is specified. This equation is not used for system optimization, but is an alternative figure of merit. NNEB summarizes the economic benefit and cost of the energy systems as they affect the Nation as a whole, without regard to which individuals the benefit and cost accrue. NNEB differs from the figures of merit for the other sectors in several aspects, as follows:

- NNEB excludes taxes, subsidies, and other intranational transfer payments.
- For NNEB, the discounting of future benefits and costs occurs at the social rate of discount rather than the private cost of capital.
- For NNEB, all costs are measured at the marginal resource cost to the Nation rather than at the prices faced by the application sectors.

SURVEY OF PRIOR ASSESSMENTS

Twenty-eight prior solar energy storage assessments applicable to the current study were identified by surveying the personnel of the Department of Energy national laboratories and the Solar Energy Research Institute. Each of the laboratories was asked for valid, accepted reports on energy storage requirements and capabilities for solar energy systems. Ten reports related to the five selected applications designated in the Phase 1 report are reviewed and summarized in "Survey of Energy Storage Assessments for Solar Applications."[3] It was not the objective of Phase 3 to determine the value of these assessment reports to the study, but to provide a basis for the national laboratories and the Solar Energy Research Institute to determine the validity of the assessments when compared to the uniform set of criteria and assessment methodology developed in Phase 2.

To standardize the presentation of technical and economic data, a common set of parameters was developed, against which each assessment was compared. First, the objectives, assumptions, methodology, and conclusions of each assessment were summarized.

Next, the energy storage system performance and technical characteristics included in each of the assessments were reviewed to determine the degree to which the following parameters were addressed:

Energy storage capacity
    (capacity rating) (MWh)
Power rating (MW)
Duty cycle (cycles/yr)

Thermal storage
    Specific heat (Btu/lb °F)
    Latent heat (Btu/lb)
Reliability

Charge/discharge time
    Charge (hr)
    Discharge (hr)
Storage efficiency (%)
Lifetime (yr)
Temperature range (°C)
Energy density
Maintainability
Safety
Environmental effects
Material scarcity
Institutional factors
Geographic locales
Solar fraction

Finally, the assessments were reviewed with respect to eight major cost and economic parameters:

Fuel price
Borrowing costs
Taxes
Solar system costs
Energy storage system costs
General economic factors
Cost goals
Figure of merit

These lists were developed from data used in various assessments and include those parameters described in the methodology report.[2] These factors, as appropriate or available, were identified for each assessment that was reviewed and are listed in the summary reviews presented in the survey report.[3] The reviews determined that the various assessments did not use a common set of parameters. Also, for a given solar energy application, the methodology of evaluation used was different, due to the several methodologies available. This is not a criticism of the reports, for each report had a different goal. It is hoped that some of the data presented in these reports will be useful for Phase 4; however, because no common data base or methodology was used, a comparison of the assessments was impossible at that time. Phase 4 will apply a common data base and methodology within a solar energy application so that a valid comparison of storage technologies can be made.

Another point to be noted is that not all applicable energy storage technologies were considered for a given solar energy technology. Phase 4 will examine and optimize the various storage technologies considered most applicable (in Phase 1) to the solar energy application.

A final point resulting from this review was that regional considerations in the assessments did not overlap to any great extent. Phase 4 will use a common set of regions with a common set of input data.

REFERENCES

1. The Aerospace Corporation, "Selection Rationale for High-Value Solar/Energy Storage Applications," Report 80-539, T. Blanchard, December 1980.

2. The Aerospace Corporation, "Uniform Assessment Methodology for Energy Storage Applications," Report 80-520, D.J. Edwards, December 1980.

3. The Aerospace Corporation, "Survey of Energy Storage Assessments for Solar Applications," Report 80-524, M.R. Harper, December 1980.

THERMAL ENERGY STORAGE CONCEPTS FOR ACTIVE SOLAR THERMAL PROCESS HEAT AND BUILDING APPLICATIONS

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ABSTRACT

The Solar Energy Research Institute (SERI) is assessing the potential of storage to enhance the capability of solar energy technologies. SERI is addressing the employment of thermal energy storage for use with active solar thermal systems to (1) produce agricultural and industrial process heat and (2) provide heating, cooling, and hot water for commercial and residential buildings. We will critique prior assessments in these applications to identify those areas where original research is needed to complete the analysis. We will compare the storage options on a standard life-cycle costing basis to determine the most promising concepts. This paper outlines our general approach and recounts the major thrusts of work in the two application areas. We will include a brief introduction to a simplified modeling procedure with and without storage. From the result of the work, we will recommend R&D priorities for the Office of Advanced Conservation Technology (OACT) at the Department of Energy.

INTRODUCTION

This task is part of a multi-lab project funded by OACT and coordinated by the Aerospace Corporation. Sandia National Laboratories/Albuquerque, Brookhaven National Laboratory, and SERI are each scrutinizing a class of storage type for a specific solar technology/application combination. A separate paper presented by Aerospace in these proceedings (Edwards & Rosenzweig)[1] reviews this project. Five areas were originally chosen for FY 1981 examination: (1) electricity for central/community applications--wind energy source; (2) same application, photovoltaics energy source; (3) residential, commercial, and light industry space heating and cooling--passive solar thermal energy source; (4) agricultural and industrial process heat (AIPH)--active solar thermal energy source; and (5) residential and commercial space heating/cooling and hot water--active solar thermal energy source. These last two applications closely track work previously done or underway at SERI and consequently were assigned to SERI. To support the AIPH work, two ongoing studies provide critical design and cost data. Thornton, et al., are comparatively evaluating solar thermal systems for providing industrial process heat (IPH). McKenzie[3] is examining thermal energy storage (TES) concepts for high-temperature process heat. Copeland and Larson[4] have previously reviewed TES subsystems for solar thermal systems. On the buildings front, Baylin[5] surveyed low-temperature TES uses. Swet and Baylin[6] postulated unresolved TES issues for building, heating and cooling.

The purpose of this task is to draw on this previous work and the large body of previous assessments to evaluate TES concepts on a life-cycle cost basis. Because prior work does not cover all of the many options of storage concept, solar thermal technology, load profile, location, temperature requirements, etc., SERI will identify such gaps and fill in as many of these as resources allow. The remainder of this paper examines (1) the approach used in the task, (2) the critical evaluation of prior assessments in the buildings study, and (3) the process heat applications work, concentrating on a simplified performance model for a solar system with storage.

GENERAL APPROACH

The problem confronting us is the awesome number of possibly interesting combinations that we could examine. To reduce this number while not eliminating good storage candidates, first we assembled a nearly exhaustive menu of the feasible storage concepts and their uses. The next section contains a schematic of this menu for the buildings applications. Then we scanned information from prior assessments to prioritize the set of options. We developed a simple three priority scheme: (1) highest priority options--must be evaluated; (2) mid priority--assess if resources allow; and (3) low priority--options generally inferior to the first two priorities. We will document this third category with the reasons for classifying each option. If time permits, we will examine these options but only after the options for priorities. We will also use value analysis to weed out undesirable storage options and determine the value that a storage subsystem or solar technology has to the purchaser of the system. Bob Copeland[7] and Mike Karpuk[8] are performing value analysis of storage options at SERI. The solar thermal cost goals committee is examining the value of solar thermal systems (Edelstein).[9] All of these studies are being monitored to help reduce the number of feasible options.

The reason for reviewing previous work is, of course, to take advantage of what has been done. The difficulty lies with the diverse and often incompatible assumptions and figures of merit used to evaluate storage systems. Where possible, we will use life-cycle costing with standard economic assumptions to normalize previous results. By using as much prior data as possible, SERI analysts will fill the remaining gaps. If only a few assessments were needed, detailed hour-by-hour simulations would be appropriate. Since the number of options is extremely large and uncertainty analysis is essential, we are seeking a simpler performance model. We are adopting one from previous work by A. Rabl[10] for use in process heat applications. We will discuss this model later in the paper. Once performance and cost data are assembled, we will evaluate them through life-cycle costing. Then we will identify the most promising systems as those with lowest life-cycle costs for particular applications and analyze those systems for R&D needs. Finally, we will recommend to OACT these future R&D needs.

In the next section we will detail our previous assessment evaluation and prioritization scheme as it has progressed in the buildings applications. The second section is a brief introduction to the simplified solar performance model to be used in evaluating process heat applications.

RESIDENTIAL/COMMERCIAL EVALUATIONS AND PRIORITIES

For heating, cooling, and domestic hot water applications for buildings, the number of storage options and scenarios to be considered is much greater than for solar process heat. Storage for solar process heat is region-sensitive only on the source side, but for solar space conditioning it is also sensitive to regional differences in load profiles. Solar process heat systems always use (or have available) oil or gas backup, while we may predicate storage concepts for space conditioning on unity-free energy fraction (no backup) or on the additional options of electric heat pumps or resistance heat backup. Space cooling systems sometimes store coolness instead of (or in addition to) heat, and the storage element is often designed for both heating and cooling service. Thus, the ways in which solar space conditioning storage can interact with sources and loads are much more numerous.

Figure 1 presents a condensed matrix of the major use and storage concept categories that have been considered in previous assessments and selected for examination in this study. The possible combinations implicit in this matrix are numbered in thousands, even when one only considers a few building types in several regions of the United States and materials and configurations for which performance and cost are fairly well characterized. Combinations that appear reasonable and competitive still number many hundreds and cannot readily be indicated on a two-dimensional matrix. As suggested by the matrix subdivisional lines, there are multiple options within each major category and multiple pairs of options in any pair of major use categories.

Table 1 is a detailed breakdown of the column headings in Figure 1, listing many of the elements from which we can construct scenarios for storage technology assessment. Clearly the number of situations in which a given storage technology might be assessed is much greater than the total number of items in these lists, even after we eliminate implausible combinations such as heating-only load in Miami. To help select a more manageable assortment of options, we compared the "popularity" of these elements in previous assessments. We found that nearly all of the elements had been addressed in at least one of the storage-related system simulation studies. Note that the priority assignments do not necessarily reflect judgments of merit (e.g., absorption chillers are not judged better than Rankine chillers).

We should explain further the study priority assignments in Table 1. Heating-only loads did not share highest priority mainly because most real solar space heating systems also heat domestic water, and DHW was omitted from previous simulations, in most cases, because of analytical or computational

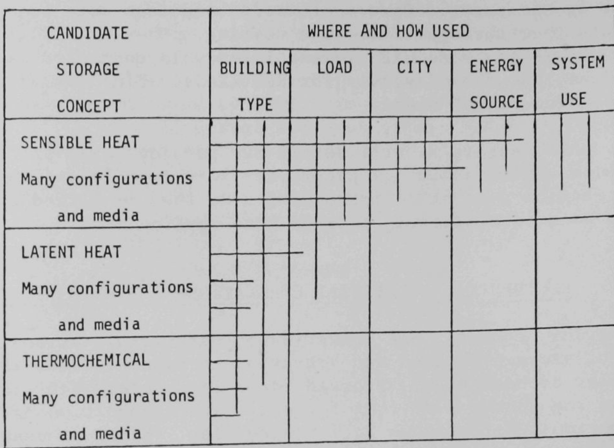

Figure 1. Condensed Matrix of Major Storage Options for Solar Heating, Cooling, and DHW

Building Type	
• Single family	(25)
• Multifamily or community	(10)
Office or other commercial	(4)
Load	
Heating only	(7)
• Heating and DHW	(12)
Heating and cooling	(1)
Cooling only	(6)
Cooling and DHW	(0)
• Heating cooling and DHW	(7)
System Use	
• Absorption chiller	(5)
• Hot side	(5)
• Cold side	(3)
Ranking chiller	(2)
Hot side	(2)
Cold side	(1)
Solar assisted heat pump	*
Evaporator side	*
Condensor side	*
Solar preheat	(0)

City	Dominant Load	
• Albuquerque, NM	C	(12)
Boston, MA	H	(9)
Fort Worth, TX	C	(3)
• Madison, WI	H	(10)
Miami, FL	C	(1)
Phoenix, AZ	C	(4)
• Washington, DC	H&C	(6)
Energy Source		
Air collector		(5)
• Liquid collector		(35)
• Flat plate		(23)
• Evacuated tube		(9)
Compound parabolic		(1)
Parabolic trough		(3)
• Solar pond		*
Winter chill		(2)
Ambient air		(2)**
• Groundwater		(1)**
Earth		(0)**
• Auxiliary		(22)
• No auxiliary		(17)

*Not counted

**Counted only for thermochemical heat pumps

Table 1. Applications of Storage for Active Solar Heating, Cooling, and DHW
(Numbers in parentheses denote prior system simulations; bullets, highest study priority.)

simplification. Similar arguments justify the lower priority for cooling only systems. There is much less current development work on Rankine chillers than on absorption systems, largely because of the anticipated unavailability of small high-performance expanders in the near term; therefore, the payoff for storage technology development dedicated to this kind of device appears less certain. Although others have paid much attention to storage for solar-assisted heat pumps, DOE's recent de-emphasis on that class of devices discouraged any compilation of pertinent prior simulations and reduced the study priority. Solar preheat, which involves the use of inexpensive low-temperature collectors and the nearly continuous boosting of their output and of storage output by an auxiliary heater, may show considerable promise in some climates and permit the use of inexpensive phase change materials such as glaubers salt.

We selected Albuquerque, Madison, and Washington because we needed to study cooling-dominated, heating-dominated, and relatively balanced load profiles, and we realized that time and budgetary constraints would probably limit the number to about three. Also, relatively few active systems have been or are being built with air heating collectors, and the kind of storage systems used with them (primarily rockbeds) appear to require relatively little technological improvement. There have been many previous assessments for solar ponds, although no one has yet assembled and characterized the documents. Of the three source/sinks for thermochemical heat pumping, we selected only groundwater despite the obvious fact that it is less universally available than ambient air.

It can, however, be more accurately and inexpensively simulated. Also, it almost certainly would exploit most fully the potential performance advantages of thermochemical heat pump/storage concepts. If the competitive position of such devices is found to be poor in this most favorable and accurately modeled situation, there will be little incentive to assess them in other scenarios.

Tables 2 through 4 present detailed breakdowns of the storage concept categories shown in Figure 1. Note that the lists in each table represent one or more matrices, so that the number of options in each category (sensible heat, latent heat, and thermochemical) is much greater than the total number of listed items.

The sensible heat options in Table 2 are, with one exception, generic in that they are not linked with a specific developer or patent and may vary considerably in detail. The exception is SOLARIS: a proprietary concept involving a steel water tank within a rockbed. For latent heat storage, the configurations are associated with specific investigators or manufacturers, as listed in Table 3. Each has unique features, and most are designed to use specific phase change materials, but some may be adaptable to other materials with different melting temperatures and applications. In Table 4 one can identify the thermochemical storage options by the combinations of absorber and working fluid and by their cyclic or continuous mode of operation. Also, one may identify a few of these options by association with the listed developers or manufacturers.

As in Table 1, the bullets in Tables 2 through 4 denote highest study priority, but with an important distinction. The bullets in Table 1 identify

Configuration	Storage Medium	Tank
• Tank (see list)	• Water	• Atmospheric
Cavern	• Brine	• Pressurized
Natural	• Water/glycol	• Single
Excavated	Oil	• Multiple
• Covered pit	• Rock	• Indoor
Partitioned lake	• Sand	Outdoor
• Aquifer	Earth	• Buried
• Natural		• Steel
• Artificial		• Concrete
• Solar pond		• Wood
• Salt gradient		• Membrane-lined
Other		
Rock bed		
SOLARIS		
Earth		
Prepared		
Undisturbed		

Table 2. Sensible Heat Storage Concepts
(Bullets denote highest study priority)

Configuration	Phase Change Material and M.P. (^{o}F)
• Bulk	Ice (32)
• Indirect heat exchange	• Paraffin (45 to 120)
ANL (ice, heat pipe)	Glaubers salt (45 to 89)
U. Minn. (ice, pumped brine)	• Neopentyl glycol (109)
• Calmac (plastic tubes)	• Sodium thiosulfate pentahydrate (118)
TESI (aluminum tubes)	Sodium acetate trihydrate (136)
• Direct heat exchange	• Magnesium nitrate hexahydrate (192)
Princeton (ice, fan)	Magnesium chloride hexahydrate (240)
• Solarmatic (immiscible fluid)	Crosslinked HDPE (266)
ITI (immiscible fluid)	
• Packaged	
• IEC (chubs)	
Valmont (plastic trays)	
Boardman (metal tubes)	
Pelletized	
• Pennwalt (coated)	
U. Dayton (form stable)	
• SERI (solid/solid)	

Table 3. Latent Heat Storage Concepts
(Bullets denote highest study priority)

the most immediately important storage *uses* or *situations*, from which we can assemble the most immediately important scenarios for technology assessment. Those in Tables 2 through 4 identify features or portions of technical concepts that are tentatively judged *most promising* and/or *most readily evaluated* among storage concepts that *already are fairly well characterized technically*, if not economically. They offer few clues regarding the more speculative combinations of technical features and materials. Presently there is too little known about these combinations, but they may yield many of the technical concepts most deserving of DOE sponsorship.

Absorber	Working Fluid	Operation
• Solid	• Water	• Cyclic
• Calcium chloride	• Methanol	• Continuous
Magnesium chloride	• Ammonia	
Sodium sulfide	Ammines	**Developer or Manufacturer**
• Metal hydrides	• Hydrogen	Chem. Energy Specialists
• Zeolite (adsorber)		• E. I. C. Corp.
• Suspended solid		Martin Marietta
Metal chlorides/decane		• Rocket Research Co.
• Metal chlorides/N-heptanol		• SoCal Edison
• Liquid		Tepidus AB
Water		E. I. R. (Switzerland)
• Sulfuric acid		Rutherford Lab (UK)
Sodium hydroxide		
Ammonium nitrate $.3NH_3$		
Sodium thiocyanate		
Lithium bromide		

Table 4. Thermochemical Storage Concepts
(Bullets denote highest study priority)

At present it appears that the problem of scenario selection and priority setting may be moot, due to possible redirection of this portion of the SERI effort. Because of current manpower limits and resulting budgetary action, we may limit the remaining work to completing and documenting the characterization of prior assessments and simulations, and to modifying the economic aspects of those studies to comply with the Aerospace Uniform Assessment Methodology. We will then base recommendations for further R&D work on this standardization of the previous studies. Work in the process heat area will not be affected. The next section discusses some of the work ongoing in that area.

AIPH PERFORMANCE MODELING

We are using the general approach described previously to evaluate storage candidates for process heat and will be developing a prioritized matrix of options as explained in the last section on buildings' applications. However, the most significant aspect of the work currently underway deals with the simplified model we are developing for evaluating the performance of solar thermal systems including storage.

The large numbers of systems to be evaluated for this study require quick modeling tools. Those we employ yield the yearly energy delivery of a solar industrial process heat (SIPH) system by reading just one or two graphs (or evaluating one or two polynomials). The accuracy is better than 5% when compared to hour by hour simulations. We optimize collector area and storage size for each system configuration before ranking the various system types.

We consider only the most important generic system types and certain standard conditions for system configuration and operation. For example, with regard to load distribution, we assume that the load is uniform throughout the day and the year, and we consider two cases: a load of 7 days/week and a load of 5 days/week. For systems without storage, we assume that the collector acts as a preheater in series with the auxiliary heat source. For systems with storage, we assume a closed-loop design of Klein and Beckman[11] (see Figure 1). Although a detailed analysis for a specific application requires optimization of many variables (e.g., heat exchanger size, pump sizes, flow rates), for our study we consider only the two most important variables, i.e., collector area and storage capacity. For the other variables we assume reasonable standard values. For example, we assume that the cost of pumps and heat exchangers associated with storage is proportional to storage capacity and that the storage cost factor is a lump sum that includes all the cost components associated with storage.

To outline the methodology, let us introduce the following nomenclature:

A = collector area [m^2]

M = storage capacity [gz]

L = annual load [gz] and

Q = annual delivered solar energy [gz]

τ_A = cost of collectors, in \$/m^2 of collector area

τ_M = cost of storage, in \$/gz of storage capacity

τ_F = cost of conventional fuel, \$/gz

C_o = fixed costs of solar system and

C_b = cost of backup system.

All costs are levelized over the life of the system. Then the total annual cost of the system is:

$$C = C_o + \tau_A A = \tau_M M + C_b + \tau_F (L - Q) \quad . \tag{1}$$

The optimum corresponds to the lowest possible total cost. Therefore, we chose collector area A and storage capacity M to minimize total cost C. This requires solving the two equations:

$$\frac{\partial C}{\partial A} = \tau_A - \tau_F \frac{\partial Q_s}{\partial A} = 0 \tag{2a}$$

and

$$\frac{\partial C}{\partial M} = \tau_M - \tau_F \frac{\partial Q_s}{\partial M} = 0 \tag{2b}$$

These two equations:

$$\frac{\partial Q}{\partial A} = \frac{\tau_A}{\tau_F} \tag{3a}$$

and

$$\frac{\partial Q}{\partial M} = \frac{\tau_M}{\tau_F} \tag{3b}$$

determine the two unknowns A and M uniquely. They can be solved if one knows the functional dependence of Q on A and M. For this analysis, we use polynomial approximations for Q that are based on the work of Rabl,[10] Klein, and Beckman.[11]

Let us designate the optimal collector area and storage capacity by A_o and M_o. Then, the energy cost of the optimized system is:

$$\frac{C}{Q} = \frac{C(A_o, M_o, \ldots.)}{Q(A_o, M_o, \ldots.)}$$

The dots indicate other variables such as load, collector parameters, and insolation.

Because this procedure is a rapid method for evaluating performance, we can address some of the vast uncertainty associated with this task. We will look at three locations (Fresno, Cal., Charleston, S.C., and New York, N.Y.); two load profiles (continuous and two shift, five days a week); two to four temperatures; and a number of solar thermal collector types. When large uncertainties exist, it is often more difficult to determine what a reasonable uncertainty band should be than to recognize whether a stated difference in value is probable. Therefore, one approach we will use to test uncertainty is to deduce from the calculation what minimum difference in storage characteristics is needed to cause a significant performance or life cycle cost difference. The validity of the conclusions of this study rests on how insensitive they are to reasonable uncertainty.

SUMMARY

SERI is endeavoring to narrow the scope of this important task without reducing its validity. Our approach is a compromise between the breadth of analysis necessary to evaluate many options and the detail of analysis needed to analyze correctly differences in system performance and life-cycle cost. This paper presents the logic and procedure for prioritizing candidates. The performance model described indicates the direction of the task with respect to performance evaluation. Such simple, fast running models facilitate the needed uncertainty analysis. As in any similar comparative study, only a wide ranging uncertainty analysis will lend credence to the results.

REFERENCES

1. Edwards, D. J. and Rosenzweig, S., "Assessment of Energy Storage for applications." Aerospace Corporation, these proceedings.

2. Thornton, J. P., Kriz, T., Gresham, J., Herlevich, F. A., Hooker, D., Comparative Ranking of Solar Thermal Systems for Thermal Applications in Industry, to be released Oct. 1981, SERI.

3. McKenzie, A., "Cost and Performance of Thermal Storage Concepts in Solar Thermal Systems, Final Design Review," Denver, CO. Stearns Roger Services, Inc., 21 Jan. 1981.

4. Copeland, R. J. and Larson, R., A Review of Thermal Storage Subsystems Integrated into Solar Thermal Systems: A Workshop Summary. Golden, CO: SERI; January 1981; SERI/TR-632-439.

5. Baylin, Frank, Low Temperature Thermal Energy Storage: A State of the Art Survey. Golden, CO: SERI; July 1979; SERI/RR-54-164.

6. Swet, C. J. and Baylin, F, Central Unresolved Issues in Thermal Energy Storage for Building Heating and Cooling. Golden, CO: SERI; July 1980; SERI/RR-721-455.

7. Copeland, R., "Preliminary Requirements for Thermal Storage Subsystems in Solar Thermal Applications," Golden, CO: SERI; April 1980; SERI/RR-731-364.

8. Hock, S. M. and Karpuk, M. E., "The Value of Thermal Storage in Solar IPH Systems," Golden, CO: SERI; December 1980; SERI/TR-731-905.

9. Edelstein, R. B., "Solar Thermal Cost Goals," Golden, CO: SERI; January 1981; SERI/TP-633-1063.

10. Rabl, Ari, "Yearly Average Performance of the Principal Solar Collector Types," Golden, CO: SERI; January 1981; SERI/TR-631-716.

11. Klein, S. A. and Beckman, W. A., "A General Design Method for Closed-Loop Solar Energy Systems," Solar Energy 22, 269; 1979.

SOLAR ENERGY STORAGE SYSTEMS ANALYSIS*

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ABSTRACT

Systems analysis activities at Brookhaven National Laboratory (BNL) related to energy storage in solar applications are described, and the purpose, methods and, where available, the results of each study are summarized. Areas of investigation include storage of electrical and thermal energy in solar total energy systems, a theoretical investigation of the value of storage, and the national fuel displacement potential of semi-passive solar storage walls. Investigations of the cost effectiveness of a spectrum of passive solar storage devices and the value of several possible improvements in these devices constitutes BNL's contribution to the Solar Applications Analysis for Energy Storage (SAAES) project.

INTRODUCTION

The last year has seen several projects underway at BNL come to fruition in the area of the systems analysis of energy storage devices in solar applications. Three of these studies have roots which predate the SAAES project, but in the interest of brevity, all recent work at BNL in this area will be discussed in this paper. The first project undertaken was an estimate of the value of energy storage devices in solar total energy systems serving residential energy loads and deriving energy from Rankine cycle, Stirling cycle or photovoltaic conversion systems. In the course of this work, questions arose as to the meaning of "value" or "breakeven costs" for storage devices in solar energy systems, and some of these questions are addressed in the second study discussed below, "Breakeven Costs of Storage in Optimized Solar Energy Systems". Passive solar energy systems for space heating have been increasing in popularity in recent years, and appear to be cost effective in some climates. We were struck by the absence of any estimates of potential national fuel savings should these techniques be widely deployed, especially of estimates based on technical modeling of such devices, so we undertook

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such a study. Due to continuing problems with the simulation model used, the results are only now becoming available, but the assumptions and methods are described in the section titled "The Fuel Conservation Potential of Solar Storage Walls". This effort flowed naturally into BNL's contribution to the SAAES effort, which is described in the final section, "Storage for Passive Solar Systems".

STORAGE IN RESIDENTIAL SOLAR TOTAL ENERGY SYSTEMS

This study looks into the future to examine the role that energy storage devices may play in residential solar total energy systems (STES), especially systems cut off from the national electric grid. The core purpose of this study is thus to establish "breakeven costs" (values) for various energy storage devices in the context of an STES, that is, to determine what the designers of such an energy delivery system would be willing to pay for various energy storage systems, given that they have the option of burning more or less fossil fuel as a backup. These breakeven costs are then compared with current production cost estimates to determine the device's potential for economic viability in this context.

Perhaps the most significant secondary topic is the method used to design "economically optimal" (minimum cost) systems. For a solar energy supply system meeting a given set of electric and thermal demands, there is a wide range of technically adequate capacities for the energy collection, energy storage, and backup devices. For a system variable, such as solar collector area, number of batteries, or size of a thermal storage tank, this method finds the component capacity at which the marginal cost of solar energy attributable to that component is equal to the marginal cost of backup energy. There are some variables, such as generator capacities, for which reliability or other constraints preclude such variation, and for some other variables the potential savings involved are insufficient to justify the effort required to "optimize" with respect to that component. This study will deal only with systems which have been optimized at least with respect to collector area and high quality energy storage capacity.

We investigate three basic types of solar energy systems: an intermediate temperature (310°C) organic Rankine cycle system with parabolic concentrating collectors, a high temperature (750°C) Stirling cycle system with a parabolic dish concentrator, and a photovoltaic system. These supply systems are matched with the loads characteristic of a set of large high rise apartments, a group of garden apartments, and a single family home. In conjunction with the Rankine cycle system, we evaluate stratified thermal storage in hydrocarbon oils with and without rock as a filler, and steam accumulators. The temperatures involved in the Stirling cycle are too high to permit thermal storage, but here and for the photovoltaic system, batteries and brief comparisons of flywheels and compressed air systems are presented.

The core of the investigation is hour-by-hour modeling of the demands and the responses of the various systems. Historical hourly weather data and electrical loads are fed into the model and thermal loads are developed from detailed models of the buildings involved; the solar system then attempts to meet these demands, charging storage if there is a surplus of energy and calling on the backup system when storage is depleted. Running totals are kept of solar and backup energy used and of other quantities of interest. Operation of the model for one "typical year" is then extrapolated over a postulated 30-year system life for the economic analysis.

For the three systems examined, Rankine cycle (RC) thermal-electric conversion, Stirling cycle (SC) conversion, and photovoltaic (PV) systems, there are always some cases where economically feasible systems achieving solar fractions of at least 50% exist, based on storage costs that have already been achieved or that are at least within the realm of possibility. Not surprisingly, these cases correspond to high fuel prices, low collector costs, and the clear skies of the Southwest. By "economically feasible systems," we mean that the minimum-cost off-grid total energy system involves the stated amount (50 to 70%) of solar energy. This does not mean that such STES are necessarily less expensive than grid-connected systems.

Uncertainties with respect to the future unit costs of fuel and solar collectors are captured by the parametric variation of these parameters. These variations in possible future unit costs give rise to variations in the area of collector and the capacity of the storage devices deployed in optimized systems. These differences between systems then produce large variations in the storage device breakeven costs. These uncertainties would render quantitative market penetration estimates untrustworthy or not useful, since potential sales would appear to vary from negligible to massive for different but equally likely fuel price path or unit collector cost assumptions. Accordingly, this study does not include projected quantitative market estimates for the storage devices.

Other conclusions reached in the course of the study are:

1. When optimized solar systems are considered, the efficiency of the storage device is the single most important variable determining the desirability of storage.

2. The high fuel costs in the Northeast do not outweigh the greater solar resource in the Southwest in determining the economics of solar energy.

3. Low temperature thermal storage was found to be attractive in two out of three systems.

Space does not permit discussion or justification of these perhaps controversial conclusions here; the study is available to those who are interested.

BREAKEVEN COSTS OF STORAGE IN OPTIMIZED SOLAR ENERGY SYSTEMS

This paper is an attempt to clarify some ambiguities in the definition of "breakeven costs" or the "value" of energy storage in optimized solar energy systems. These ambiguities have arisen in the course of analysis of the possible uses of energy storage devices which are now under development, funded by the Department of Energy (DOE). Discussion of the ambiguities requires a clear understanding of the concepts involved, so I begin with some definitions.

I will be discussing solar energy systems which are designed to meet well defined loads under specified weather conditions. Although a wide range of components can actually be used in such systems, a configuration consisting of collector area, storage capacity and a backup system which burns an amount of fuel dependent on the collector area and storage capacity will prove sufficiently detailed for this discussion. The amount of fuel actually consumed is assumed to be determined either from experiment or from simulation. The discussion applies to a wide range of solar energy systems, including hot water, space heat, process heat, or electricity. The range of storage devices is correspondingly broad.

Initially, we take the "breakeven cost" or "value" of storage (or of any other component) to be simply the price a designer of optimized systems would be willing to pay for the component in question. However, a hitch has already arisen: If we are seeking a value, we do not know the cost of the component, so we do not know how to optimize the system. A partial answer is that we can have systems optimized with respect to the other components, the collector area in particular, as long as we know the collector costs. It is important to remember, however, that the amount of collector in an optimized system, and many other characteristics, will depend on the amount of storage in that system, whether we know what the storage costs are, or finding what it is worth. Changing the amount of storage will change the technical and economic characteristics of the optimized system and thus the environment in which the storage is to be evaluated.

However, for any given configuration, we can unambiguously define the marginal value of storage as being equal to the value of the fuel displacement and other savings attributable to a small incremental increase in the storage capacity, divided by that increase in capacity. Since a value for storage is sought, the calculation must not include any costs for the storage or for the increase in storage capacity.

We have already come to the first significant ambiguity. Since the value of storage depends on the amount of storage in the system, it is not well defined even in a single system. Changing the amount of storage by any substantial amount will, for an optimized system, change the amount of collector and the amount of fuel consumed, resulting in a change in the fuel that would be displaced by an incremental amount of storage and hence changing the value of storage. It is one of the purposes of this paper to examine the nature of the dependence of the value of storage on solar fraction (or, equivalently, on the amount of storage in the system) and to suggest some conventions to deal with this ambiguity.

Some future costs, most notably the costs of collectors, may be significantly altered by R&D funding decisions made now in response to analyses similar to the type I have been discussing for storage devices, but where the costs of storage are assumed known and breakeven costs for collectors are sought. This raises the question, how shall R&D funding directed at lowering component costs be allocated between collectors, storage and (possibly) other components? Although such decisions involve much more than analysis, it is good to know how much analysis can tell us about the issue, so that discussions can be based on clear understanding of the technical issues.

THE FUEL CONSERVATION POTENTIAL OF SOLAR-STORAGE WALLS

In this paper we consider the oil, gas and electricity displacement potential of "passive" solar energy storage devices in residential and commercial space heating applications. To carry out this study, it was necessary to characterize and model the U.S. building stock to design appropriate collection storage devices and to estimate their performance through simulation. We then combined these performance estimates with cost projections to determine probable costs of delivered energy and combined the performance estimates with housing stock and levels of possible implementation to determine maximum possible fuel displacements.

We divided the housing stock among several model types -- single family detached of one or two stories, single family attached, and low rise and high rise multifamily structures. Commercial buildings were apportioned between low rise and high rise structures. An appropriate model for each type of building was adapted for computer simulation. The models for buildings existing in 1980 were adapted to reflect the extensive conservation retrofits we expect between now and 2000 (the base year used here) and new housing was modeled according to similarly exacting standards. This was done to ensure that our solar devices would not be supplying energy for which there would actually be no demand due to conservation retrofits.

The performance of the houses, with and without the collection storage devices, was determined from hourly simulation over one heating season using the DEROB system from the University of Texas at Austin and SOLMET weather data for typical years. Different simulations were carried out for each of nine regions of the country. In each case, the energy saved by buildings equipped with the devices (compared to buildings without them) was ascribed to the device; fuel saved can be computed by dividing by the furnace efficiency, taken as 70%.

Performance of the devices varied dramatically with climate, from about 1-16 MMBtu/yr for single family houses. This corresponded to a range of from

7,000 Btu/ft^2 of collector per year in Seattle to over 65,000 Btu/ft^2/year in Albuquerque. Device performance in commercial buildings was much poorer, delivering less than 1/3 the energy obtained in residential buildings and having a much smaller effect on the total building load. Most commercial buildings are vacated early in the evening, leaving little demand for the stored energy until the next morning when much has been lost. Due to this poor performance and the apparent lack of need for storage in these circumstances, commercial buildings were dropped from further consideration in this study. At best, even the performance of the devices in residential applications must be considered fairly poor -- only from 5-20% of the solar energy striking the device ended up in the house. There are two major reasons for this, and every reason to think that appropriate research and development could improve performance considerably. The first reason is the large (about 25%) losses to reflections in the glazings. The second is high thermal losses through the glazings during the days, and to some extent at night. These problems, and potential of various cures, are the subject of current research.

We determine the maximum energy that could be displaced on a regional basis by combining our performance results with disaggregated estimates of the national housing stock, both that are currently in existance and that are anticipated to be retired or constructed between now and 2000. These projections necessarily included some quite arguable estimates of the number of buildings in each sector suitable for solar energy with respect to orientation, design features, shadowing by trees, or other buildings and other factors. The results come to a maximum feasible oil and gas displacement of a few tenths of a quad.

In conclusion, we have found that a significant, but not overwhelming, amount of space heat can be supplied by devices based on currently available technology. The primary problem is clearly poor performance of the devices, and improvements in efficiency can be expected to improve the outlook for passive solar collection-storage devices significantly.

THE "SOLAR APPLICATIONS ANALYSIS FOR ENERGY STORAGE" PROJECT

"Summaries and Comments on a Selection of Technical and Economic Assessments of Residential Applications of Passive Solar Energy"

The report is the summary of a search for studies concerning residential, commercial and light industrial space heating and cooling whose energy source is passive solar thermal. The intent of this review is to summarize studies which are relevant to our assessment and identify the information in these studies with potential applicability. It is also noted that there are relatively few applicable studies on passive solar cooling and rock bed storage and that the bulk of studies summarized pertain to thermal storage walls and direct gain systems for passive solar heating in the residential sector.

For some studies it was possible to utilize the descriptive framework embodied in the Aerospace Corporation's, "Survey of Energy Storage Assessments for Solar Applications". This approach, however, has excluded the preparation of standardized tables summarizing performance, cost and economic data since none of the studies reviewed could offer sufficient data to make these tables meaningful. It is our intent to evolve a common set of parameters during Task 2 which will be comprised of an amalgam of data from our own studies and those reviewed. Information or techniques from reviewed studies which are relevant to our assessment are discussed as an addition to the above framework under the heading, "Comments".

For those studies which are not amenable to the above framework the approach is a written summary which highlights significant information and discusses its application to our study. Some sets of studies, particularly those conducted by Los Alamos Laboratory, involved the same underlying assumptions and methodology. For these cases, we first give a detailed description of one study. A list of similar studies is then presented at the end of the description.

"The Comparative Economic Performance of Selected Passive Solar Heating and Cooling Technologies"

The economic performance of selected passive solar heating and cooling technologies which incorporate energy storage is assessed using a set of uniform assumptions and methodologies. The technologies assessed are:

- A ventilated trombe wall, applicable to industrial and commercial uses where large ventilating loads dominate building heat losses.
- A solar roof pond for heating and cooling a medium size combined factory and office.
- Night effect cooling of a large multi-story office building using concrete floor slabs as thermal storage.
- Night effect cooling of residential and small commercial dwellings by way of modifications to an existing, optimized rock bed solar heating system.
- Various trombe, direct gain and clerestory configurations.

Where it is reasonable, a given system is assessed at more than one geographical location. Results are obtained in the form of both payback period and net present value for residential applications, and in terms of net present value only for industrial/commercial uses.

Results indicate that ventilated trombe walls, solar roof ponds, and certain night effect/floor storage strategies are cost effective, while night effect/rock bed cooling is not. Results also show that while direct gain out-performs trombe walls in most parts of the country, both direct gain and trombe walls usually produce a net savings in the residential sector. Generally however, tax regulations result in a net economic loss for direct gain and trombe walls used to heat industrial and commercial buildings.

Future Work

For technologies with adequate capital cost information available, we will determine the optimal passive solar energy storage system configuration by using the prescribed discounted payback calculations set forth in "Uniform Assessment Methodology for Energy Storage Applications." An example would be calculation of a payback period for a water wall affixed to a wood frame building and consisting of extruded plastic glazing, plywood enclosures, and some form of mounting apparatus.

As part of the assessment, we will investigate improvements which would potentially improve the performance and cost effectiveness of those storage technologies already examined. These improvements will include characteristics of phase change materials, low emissivity surfaces in collectors and anti-reflection coatings on glazings.

For "improved technologies," i.e., those which involve modification of base case technology, we will use breakeven cost analysis. Thus, we will use estimates of the performance improvements resulting from the technical improvements to determine the "value" (or "breakeven cost") of the improvement. This methodology is selected due to the highly uncertain nature of capital and construction costs for improved technologies which do not yet exist. Breakeven cost analysis is particularly useful since it avoids specification of unknown component costs and sets an upper limit for total system costs. Certain costs (e.g., fuel) may be parameterized to determine impact on total system costs and breakeven costs. An example where breakeven cost analysis might be used is in assessment of an as-of-yet undeveloped anti-reflective coating for glazed surfaces. Since accurate capital costs cannot be ascribed, it would be more useful to have an upper limit for economic feasibility.

REFERENCES

1. Leigh, R.W., Storage in Residential Solar Total Energy Systems, BNL 51230, Dec. 1980.

2. Leigh, R.W., Breakeven Costs of Storage in Optimized Solar Energy Systems, Jan. 1981, (in draft).

3. Leigh, R.W. and Pouder, R.W., The Fuel Conservation Potential of Solar Storage Walls, BNL 51277, Dec. 1980, (to be published).

4. Pouder, R.W., Summaries and Comments on a Selection of Technical and Economic Assessments of Residential Applications of Passive Solar Energy, BNL 28985, Feb. 1981.

5. Rutter, W., The Comparative Economic Performance of Selected Passive Solar Heating and Cooling Technologies, March 1981, (in draft).

STORAGE FOR WIND AND PHOTOVOLTAIC SYSTEMS

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The goals of this study are to determine the value of storage, as provided by batteries and flywheels, in the following solar application: building electrical services, in a stand-along configuration featuring either wind turbines or photovoltaic panels as the energy source, and with an on-site generator for back-up energy. The Uniform Assessment Methodology developed by Aerospace Corporation will be used in the analysis.

This project was initiated in January 1981, therefore, a progress report was not available for the conference.

CHAIRMAN'S SUMMARY OF PANEL DISCUSSION

SESSION I
STORAGE FOR SOLAR APPLICATIONS

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The discussion centered around two major issues. The first was related to the nature of input data into the codes used in performing value analyses and cost estimates for storage in solar applications and the availability of models for storage systems. The uniformity of input data was considered important in making joint cost estimates where, for example, not only the solar collector costs must be considered, but the changes in the roof structure as well. It was pointed out that part of the methodology included the use of industry accepted kinds of cost estimating techniques, applied to conceptual designs offered by organizations proposing an advanced storage system. The results are then submitted to developers for review and comment and then returned to the proposing organization for a second iteration, etc. Peer reviews were conducted to assure that the techniques used were comparable across various solar technologies. It was agreed, however, that economic studies for mature solar technologies were easy to perform. It is the emerging technologies such as advanced batteries, thermochemical systems, etc., that lack good cost estimates. For such systems, the semi-qualitative nature of the study must be emphasized. It was mentioned by one participant (C.J. Swet) that a surprisingly large number of models exist for advanced storage systems, such as thermochemical systems in the U.S. and abroad.

The second issue revolved around the importance of dealing with buffer storage in solar thermal power generation. Buffer storage is defined as a transient, such as a cloud cover, that lasts from minutes up to several hours. One of the problems inherent in evaluating buffer storage is not just hour by hour or minute by minute simulation, but rather the rapid switching to charge or discharge modes in storage that can affect the entire system. This seems to be one area where very little has been done. According to a recent National Academy of Sciences study, insufficient attention has been paid to the acquisition of information necessary to design properly and integrate buffer storage into solar conversion systems.

In addition to the above major issues, the discussion covered the following:

1. Proper matching of a solar technology to its end-use was strongly emphasized with due consideration given to maximizing the availability

of energy according to the second law of thermodynamics. For example, one should not generate and store thermal energy with a wind turbine whose output is mechanical/electrical.

2. Special cases may exist where the strong need for energy independence or emergency power requirements would lead individuals to accept higher than normal storage costs. As part of the solar thermal aplication study, it was discovered that industry is willing to give up a certain amount of their criteria, for example three percent of the rate of return, or a year or two of payback, in order to get a system from zero storage up to six hours worth of storage.

SESSION II:
INFORMATION MANAGEMENT AND R&D EVALUATION

TECHNOLOGY INFORMATION SYSTEM REVIEW

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ABSTRACT*

The Technology Information System (TIS) is a new generation, dedicated information machine established to support the DOE/ACT Technical and Economic Analysis program. Capabilities include nationwide management of bibliographic and numeric data files, interactive modeling, electronic communications, and distributed networking. These capabilities are self-guided and permit also those not intimately familiar with computers to create their own data files, graphics, and procedures. In addition, TIS provides electronic mail and conferencing, and connects automatically in a controlled manner to other information centers and computational resources. TIS is accessible from remote computer terminals at 300-1200 bps over commercial, FTS, and WATS telephone lines, the ARPA computer network, and in the near future also TYMNET/TELENET. TIS is co-sponsored by the Seasonal Thermal Energy Storage program and other organizations which contribute to its overall capabilities. An on-line directory to major federal and state information centers, and automated dial-up to some of them, are in preparation.

INTRODUCTION

The Technology Information System (TIS) is being developed as part of the Transportation Systems Research (TSR) program at Lawrence Livermore National Laboratory (LLNL). The TIS project has for the most part been sponsored by the Technical and Economic Analysis (TEA) Branch of the U.S.

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Department of Energy (DOE), Office of Applied Conservation Technology (ACT). The goal of TIS is to provide ACT and its contractors the capability to readily access, develop, and utilize information needed in the R&D decision-making process and the conduct of resultant R&D projects.

Our objective in this paper is to: describe the status of TIS; show work accomplished during the past year; and show the implication of present efforts on the future TIS system. To accomplish this objective, we discuss our general approach to TIS development, describe present TIS capabilities and the relevance of present efforts, show the application of TIS to STES, and outline the implications of present work and future plans.

APPROACH

Understanding our basic approach will provide insight as to why many of the current TIS developments are underway and how these contribute to overall capabilities development. To formulate the approach, we ask "What does the user desire?", and "What are the limitations?" Anticipated responses to the questions allowed us to formulate the overall objectives. Support from various organizations contribute to these objectives.

A potential user wants his information system to give him the information he needs, when he needs it, in the way he wants to see it, and requiring little effort to get it. Each of these points has certain system implications. To give him the information he needs requires that "basic" information is available and it can be reduced to the user's requirements.

There can be many sources of basic information. There are sources within the system. The user may have his own private database which is available to him or his local technical community only. Also within the system there may be a public database which can be accessed by the entire user community. There are also important sources which are external to the system at information centers or databases at remote locations. An important source of information is people. A user wants access to all of these sources.

But, basic information is of no use to a user unless he can reduce it to the information he needs. Therefore, processing tools, models and other appropriate software, must be available. They may reside internal to the system or at external sources. To obtain information when a user needs it requires immediate access to those information sources, as well as the ability to immediately initiate a request, and receive an immediate response by the system. Information is provided in the way he wants to see it when capabilities are available to tabulate information, display information graphically, generate and edit text and data, etc.

Finally, to obtain information with little effort means that "smart" software must be used to eliminate the need for prior education, i.e., the system is self-prompting. It also means that the system must be easy to use, i.e., it is simple and logically structured. Finally, it cannot be laborious to use, i.e., there are few commands. This requirement is different for new or infrequent users, and those who are frequent users.

All these system requirements cannot be realized. We are developing TIS by imposing realistic constraints on these general system characteristics. In this system the user has access to a public database contained internal to TIS. Not everything he needs, however, will be contained within that database. There are very specific datafiles and processing software that he may place in his own private database. There is also other information better retained at remote locations. Where information exists but is not directly accessible, a directory of the "where's" and "how's" associated with obtaining that information is provided. Finally, the system has recognized people as an important information source and provides the capability not only to access those important sources, but to provide an effective exchange.

There are two aspects to TIS development. First there is capabilities development. This is essentially independent of the application of a particular user community. Secondly, there is applications development where the specific information of a user community is placed on the system and the capabilities tailored to that particular application.

Because the development of capabilities is independent of application, we have solicited and obtained the support of many organizations (DOE/TEA, DOE/STES, DOE/TIC, Interagency Information Exchange Group, DOE/BESD, and LLNL/Laser). Each of the organizations have specific requirements but each of the efforts contribute to the overall capabilities development.

There are ACT programs (ACT/TEA, ACT/STES, LLNL/TSR) for which applications development is being accomplished. For these programs, specific user communities, dealing with specific technical information, are using TIS.

The basic approach to TIS development is to develop specific TIS capabilities for many different organizations where each contributes to the overall capabilities and applications development of the system. The status of TIS capabilities and its use by STES illustrates the success of this approach.

TIS CAPABILITIES

Capabilities of the Technology Information System (TIS) provide nationwide bibliographic and numeric database management, interactive modeling, electronic communications, distributed networking, and graphics. These capabilities are self-guided and are used successfully by those not intimately familiar with computers.

GENERAL CAPABILITIES

TIS is a new generation, dedicated information machine. Programmatic information is kept on TIS. When additional information or numeric data are needed, TIS connects to other information centers, in an automated and controlled manner. Users simply specify the target name of the desired resource.

In addition, since much of the daily work in R&D is being documented on electronic word processors, we established the capability of linking with several of these machines for transfer of information and data to and from TIS. Translation of formats is carried out by TIS as required.

Analysis, synthesis, and post-processing of information and data speed up progress, increase productivity, and transfer technology. TIS gives this capability to each user. The user can define and create his own data files, reports, graphics, and communications by activating selfguiding routines. Initially, the results of your work belong to you alone. A permit command shares the data or displays with someone else, co-workers, or for general use by others.

The system is accessible from any telephone at 300 or 1200 bps, over the ARPA computer network, and soon also over the world-wide TELENET/TYMNET system. FTS and WATS lines are provided for cost-effective use of communications and convenience.

There are about 170 authorized users throughout the country. Electronic communications and the automated access to other information centers are available to all users.

DATABASE MANAGEMENT CAPABILITIES

Information is the total of textual and numeric data displayed in a meaningful manner. Most systems specialize in one or the other. Also, most database management systems initially require a computer programmer or analyst. The database is turned over to the user for retrieval and updating. Whenever special features are required, the services of a programmer are again needed. The Technology Information System (TIS) offers not only this capability but the capability of direct database management by its users without programmer intervention. This permits the use of TIS as an extension of the yellow note pad, or desk calculator. Thus,we distinguish on TIS two categories of databases, public and private.

The public databases are ,therefore, intended for general use in support of a particular program. The information in these databases is displayed in a hierarchical manner and can be selected with simple specification of an "Option Number." Its information content can be viewed, used, and extracted as required. Temporary changes to this data can be done for display or for ad hoc exploratory calculations by any users. When such changes are made, they are annunciated in the input record. Permanent changes can only be made through the Database Administrator.

The private database offers the additional capability of database creation. The create command starts a self-guided routine that permits you to establish a hierarchical index for information in your own database system. You can specify and name the datafiles and are prompted to describe each data field, the units of measurement, and an identifying acronym.

Data is generally entered key-to-disk, using a menu-driven form that flashes on the cathode ray screen. Magnetic tapes are used when larger volumes of data are involved. Data can also be transfered over telephone lines or over the ARPA computer network at effective transmission rates up to 36,000 bps.

Key-to-disk operations are greatly helped by menus for on-line prompting. These display formats can be activated by self-guided makeform routines which are called into action by name. The data fields are explicitly called out on the screen. Inadvertantly entered text characters lock the terminal keyboard and signal the error.

The update command is used to append, replace and replicate data. It provides help instructions for the searching of erroneous records which can then be corrected in a systematic manner.

The display and extraction of information or numeric data can be carried out in two ways. First, each public datafile comes equipped with display formats, also referred to as reports. These can be activated by name. Reports can be graphs or tables. You can choose those that fit your terminal. Second, you can create your own reports using the print or plot commands. These routines guide you to name the datafile, the datafields to be printed, summed, labeled, ordered, foot-noted, etc. Plots can be seen in black and white on Hewlett-Packard 2648 terminals, or in color on HP 7221 color plotters. An interface for graphics display on other terminals is being prepared.

Numeric data can be extracted for later use through use of the print command and then saved in separate files.

Each datafile in the public databases is described with reference to its origin and last date of update. It also contains pre-formatted display formats by name. However, the user may use Boolean logic and algebraic notation to define new virtual data fields, and to create new reports and graphs following self-guided TIS routines. These patterns can be combined with text for reports which, when activated by name, initiate an automated sequence of commands.

Reports, graphs, and sequences of presentations can be used initially only by the creator. A positive permit command allows sharing the information with selected co-workers, or the user community. A user only has availability of those datafiles and display patterns to which he has been given access.

In addition to routines cited in the TIS User's Manual, many other powerful UNIX utility routines are available. They appear in the UNIX manual and other supporting literature.

Help is available on-line for most programs. Commands with many parameters give help during execution. You may type "help" at each step to receive guidance for the next question to be answered. We offer also on-line tutorials.

MODELING

The execution of models can be carried out interactively or in the batch mode in three ways:

- The model may reside on TIS which controls its input and output.
- The model may be activated by TIS, but prompting remains under model control.

- The model may reside on another computer elsewhere in the country, controlled by TIS with regard to input or output.

The first method is represented by models developed at LLNL for performance prediction of electric and hybrid vehicles. Originally, these models were used in the batch mode.

An interactive script has been written that describes each parameter and prompts the user for the selection of parameter values by category or value. The descriptions and the interactive script for each model are now in a small datafile and part of the overall Transportation Systems Research database. The potential user can familiarize himself with the model by selective reference to the appropriate Option Number. To run the model, he is prompted to select the required parameter categories or give his own values. When answered , the data is extracted from the individual datafiles and presented for viewing and confirmation. Ad hoc changes can be made at this time. Execution is in real time and the results are presented in tabular form or as graphical output. Efficient interactive input methods are available for users requiring repeated execution of models.

An example for the second class of models is the EXXON econometric model for electric cars. It is available on TIS. Original prompting devised by EXXON is used. TIS is the controller for the model run and provides a convenient means of execution. Any model which can be compiled and processed on the PDP-11/70 machine can be integrated into TIS in this manner.

With the third type of modeling capabilities on TIS, the model is executed on a foreign host computer under TIS control. TIS connects an authorized user to the distant computer automatically and activates the named model. Examples are the Electric Vehicle Model (ELEVEC) at Jet Propulsion Laboratory and the "CCC" Thermal Aquifer Model. "CCC" was moved from LBL to the SERI computer. It requires a CDC-7600 and considerable time to execute. In this case, TIS is preparing the input file for "CCC" execution at SERI.

Modeling requires programming. The major languages available on TIS are:

FORTRAN IV	BASIC	APL	DC
PASCAL	SNABOL	"C"	MB
MACRO II	LISP	RAFFOR	AS

Several powerful text editors are supported by the UNIX program and provide on-line editing capabilities for a variety of different terminals.

Several statistical and graphical analysis routines are available on TIS. In graphics, we have a number of programs which permit on-line input in a prompting manner. Creation of barcharts, piecharts, and milestone charts are examples. Graphs can be prepared in color as hard copy or directly as viewgraphs. Once created and named, the resulting format file can be released for use elsewhere and printed near-instantaneously cross-country on compatible equipment.

COMMUNICATIONS

TIS offers the following communications capabilities:

write	- is a diascript between two users.
link	- provides tutorials for one or a group of users.
electronic mail	- serves the entire user community, inclusive of voting and the joint preparation of reports.
interconnection to word processors	- permits the transmission of letters and reports via TIS.

The write command is a diascript between two users logged in on TIS at the same time. The write command, followed by the recipient user's name, prints an alert message at his terminal. It requires a similar confirmation. The message is then typed. A signal can be typed to indicate the end of a question or statement, inviting the response, and so forth.

The link command is used for tutorial purposes. By previous agreement, it permits any two users to work together. One user becomes the teacher and works in the student's account. A dropfile can be created for subsequent perusal. This capability is being used by TIS staff for cross-country tutorials. They are especially effective when used with a voice phone, permitting the student to see and hear instructions simultaneously. Special arrangements can be made for class tutorials.

Electronic mail (em) permits you to send and receive messages, to answer and forward mail, to issue group mailings, and to file correspondence in a mail filing system of your own. Some 26 different options are available to compose and edit messages and reports, correct spelling by reference to the on-line Webster's dictionary, send blind copies, and check whether an addressee may have already read your mail. Of course, you can delete all mail. On-line help is available for all options. Most commands can be executed by their starting letter.

Interconnection with Text Processors. We established the capability to connect TIS with several word processors: WANG, LEXITRON, QYX. A connection to the FOUR PHASE system is planned. When used in conjunction with electronic mail, any letter or report typed on a word processor can be sent near instantaneously to its destination. Incompatible control characters among some of the different word processor systems are translated by TIS as required.

DISTRIBUTED NETWORKING

Distributed networking connects and uses other information centers and computers in an automated and controlled manner. By providing access to 22 other centers, we have vastly increased the information content and capabilities of TIS. Arrangements for connections require only one contract with TIS. Users on TIS are granted access as needed for the duration of their work. Audit files keep accurate records of all transactions. Individual users of TIS need not learn the access protocols, passwords, or peculiarities of the foreign host computers. They simply select the information center by Option Number or by name.

TIS can view or extract information in files for subsequent processing and use where legally permissable. A cogent example is our interconnection to the extensive DOE/RECON information system. All citations retrieved can be placed into a file, aggregated, and processed interactively, on-line for the creation of subject and author indexes, or for topical concordances. We expect to have similar links soon with NASA/RECON and with the unclassified Defense Technical Information Center (DTIC). These files are in the public domain and can be used to establish comprehensive, well-indexed bibliographies, now carried out more laboriously. Where required, citations can be complemented with key-to-disk annotations about their relevancy and ranking. Requests for full-text copies can be issued automatically. Citations can be augmented with numeric or descriptive data derived from the reports. This capability is equally applicable to numeric data and offers the opportunity of data aggregation from different sources into one topical summary.

This brief summary of TIS capabilities is further explained in the TIS User's Manual. Some of our users may find these capabilities too powerful for their needs. Others, more familiar with computer operations, may prefer to use TIS as a computational facility. We are striving continuously to be responsive toward both user requirements. The manner in which STES is using TIS is described in the following section.

APPLICATION OF "TIS" TO THE SEASONAL THERMAL ENERGY STORAGE PROGRAM*

The Seasonal Thermal Energy Storage (STES) Program, which is managed by the Pacific Northwest Laboratoy (PNL) for the U.S. Department of Energy (DOE), is a large, multi-year program designed to demonstrate the storage of thermal energy on a seasonal basis, using surplus heat or cold. The STES program involves many industrial, university, and government contractors who are distributed throughout the United States. Effective management of this large program with its geographically-distributed components depends upon the availabiity of accurate and timely information. The STES-TIS is intended to fill this need. The system provides an efficient means for STES subprogram to exchange information.

Unlike other information systems that offer only bibliographic, financial, numeric, or computational services, TIS combines all of these different resources into one powerful information system. We find especially useful the interactive access to models, electronic mail and conferencing, distributed computer resources, and databases related to energy storage in general. We find the system to be highly oriented and self-guiding. It can be used by program managers, scientists, engineers, and support staff without previous computer experience.

STES was given authority by LLNL to administer the STES-TIS database and to admit to or remove users from access to other information centers and computers. This has worked out very well.

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* This is an extract from the paper: "The Seasonal Thermal Energy Storage Technology Information System," published as PNL-SA-8800 by L. S. Prater, J. R. Eliason, and V. E. Hampel, presented by Leigh Prater at the Eighth Energy Technology Conference, March 9-11, 1981, in Washington, D.C.

PHYSICAL ASPECTS OF SYSTEM DEVELOPMENT

Development of the STES-TIS was initiated in June of FY 1980. Remote terminal systems have been installed and are now serving the STES Program office at PNL. In addition, communication capabilities were added to the Qyx word processors, used by the STES program secretaries, to enable the word processors to operate as remote terminals. Secretaries can transfer documents from the word processors directly into the STES-TIS and to other system users via the TIS electronic mail. This capability has vastly improved communications between the STES Program office, our contractors, and DOE/ACT headquarters.

The success and viability of the STES-TIS depended on reliable communications lines between LLNL and PNL. The only viable communication option appeared to be communications over phone lines, which can be somewhat noisy. Off the shelf error controlling units were procured by LLNL to eliminate transmission of stray characters on both ends of the line. These units have allowed reliable communications at 1200 baud rates. This rate is sufficient for most of our work including color graphics. Most of the STES contractors use phone lines to access the STES-TIS.

ORGANIZATIONAL STRUCTURE OF THE STES-TIS

STES-TIS is structured in a very logical and orderly hierarchy allowing inexperienced users to obtain the desired information without in-depth knowledge of the database structure, or the operating system's command language. The hierarchy provides a guide by which a user can navigate through the available datafiles. When a user enters the STES-TIS, he is automatically placed at the top level of the hierarchy, and the resources available at that level are listed. The highest level of the hierarchy contains the following resources:

0 STES Technology Information System
- 1 STES Administrative Information
- 2 Aquifer Demonstration Program
- 3 Seasonal Storage Technology Program
- 4 STES Library & Bibliography
- 5 Integrated Computer Resources
- 6 News
- 7 Electronic Mail

The user may select any one of these options. If, for example, a user selects option number 1, he will be dropped into the next level of the hierarchy, and the following directory will be shown:

1 STES Administrative Information
- 1.1 STES Program Description
- 1.2 Conference Agenda
- 1.3 Mailing Directories
- 1.4 STES Program Management

The user may now select any of these options and continue down the hierarchy, or he may return to the top of the hierarchy and may pursue another branch. Access to any level can also be carried out directly. Methods that can be used to find and extract information from the STES-TIS are described in the STES Database Tutorial (Gallo, 1980).

INCORPORATION OF DATAFILES AND MODELS

The hierarchy provides the framework necessary to incorporate adminstrative, bibliographic, computational, and communications resources. The project status of each of these resource types is discussed in the following paragraphs.

ADMINISTRATIVE

Several administrative datafiles have been entered into the STES-TIS. One file contains details about conferences, names of STES staff members who attended or presented papers, and information about the papers. Another administrative datafile contains two types of news: 1) weekly highlights, which are short reports describing the important events of each week, and 2) newsletter articles, which are compiled, printed, and distributed on a quarterly basis.

BIBLIOGRAPHIC

The STES-TIS contains bibliographic data from the Seasonal Thermal Energy Storage Library. These bibliographic data were transferred into the TIS computer from a Wang word-processing system; checked for validity and were converted to the proper format; and then checked by the STES librarian for completeness and accuracy. The library datafile now contains over 1700 citations and is updated regularly.

The STES-TIS can be used to conduct customized, on-line searches of the bibliography on any field of the citation, including author, title, publisher, publication date, keywords, etc. Methods for searching the bibliographic datafile have been documented by Kawin (1980).

The citations identified as the result of a search can be printed out in a variety of formats. The entire bibliographic datafile can also be printed out on a high-quality printer to produce a camera-ready copy of the STES Bibliography for publication.

Each citation contains fields that can be used by the STES librarian to keep a record of the status of the document that the citation represents. The ability to keep an on-line record of library transactions eliminates the need for maintaining voluminous hard-copy files.

COMPUTATIONAL

The STES Program is developing several models that could potentially be put into the system, including both economic and hydrologic models. Some of these models are too long and complex to reside on the relatively small PDP-11/70 computer housing STES-TIS. In these cases, the STES-TIS can be used as an automated gateway to computer resources which can accommodate them. One of the complex hydrologic codes has been implemented on the large computer (CDC-7600) at the Solar Energy Research Institute. Connection is made automatically, with the STES-TIS acting as an interface so that the user does not have to know the telephone number, password, or protocol of the other computer. Other computer resources available through the STES-TIS, or used by STES, include PDP 11/44 and PDP 11/70 at PNL, DEC 1380 at MIT, DEC 1390 at SRI and PDP 11/70 and VAX 11/780 at LBL.

Implementation of the STES models on the STES-TIS makes them available to a wider community of users, thereby encouraging transfer to the commercial sector. LLNL can also assist in converting the models to interactive use, allowing users to run the models without having intimate knowledge of the codes.

COMMUNICATIONS

The STES-TIS offers many communications capabilities. Electronic mail is used to leave messages in the "mailbox" of users, who are notified when they enter the system. The STES-TIS also has a conferencing capability, whereby users solicit responses to a message from other users. Terminal-to-terminal communications are also possible, using the "write" and "link" commands. The communication capabilities of the STES-TIS are described more fully by Hampel and Schriebman (1980).

STES-TIS communication capabilities have allowed the program office at PNL to keep in close contact with all of the contractors. These capabilities allow instantaneous transmission of messages and eliminate the delays in conventional mail. We still send signed copies, but they often serve primarily to confirm and formalize the messages sent electronically. Rapid transmission of information has led to more efficient management of the STES Program.

TIS - WHERE DO WE GO FROM HERE?

The main question faced by a potential user seeking information is where to find it and how to get it. In response to these demands, we are installing on TIS an on-line directory to major federal and state information centers with automated , controlled dial-up where programmatically required. This expanded capability, supported by the Technical Information Center (DOE/TIC), is being developed in preparation of an integrated information network. User interaction, evaluation, and feedback is a dominant aspect of this development. The prototyping is planned in three steps:

1. On-line Directory & Automated Access Controls.

2. Standardization of Access & Post-processing Techniques.

3. Transfer of TIS software to other centers.

The on-line directory will make use of information and data gathered by the University of Tennessee on behalf of DOE/TIC. Initially, a description of each center and indication whether it is accessible by commercial communication networks are being proposed. Thereafter, accounts will be opened for those centers where user demand and readiness to pay for the information are present. Finally, the actual information resources, e.g., data files/models, etc., will be listed on-line with direct connection where feasible.

The standardization of access and post-processing techniques includes the heuristic expansion of the TIS command language for bibliographic and numeric data, post-processing of retrieved citations and numeric data, and implementation and testing of the proposed ANSI/ISO X3L5 data exchange standard.

The transfer of TIS software to other installations is expected to be practical in light of the growing popularity of the "C" programming language compilers on other computers and their emulation of the UNIX operating system. The Meta-Machine implementation on TIS provides an extensible and flexible environment for the prototyping of the integrated information network. It is expected to be capable of effective interaction in several command languages and user languages other than English.

DOE/TIC and other supporting organizations contribute to the expansion of the overall capabilities for the TIS user community. Application forms for the use of TIS are included in the TIS User's Manual.

REFERENCES

1. Gallo, Laurie E. 1980. "STES Database Tutorial." Supplement No. 1 to M-0112 (Draft), Lawrence Livermore National Laboratory, Livermore, CA.

2. Hampel, Viktor E. and William G. Rabe. 1980. "STES-TIS Technical Information System." UCRL-85064, Lawrence Livermore National Laboratory, Livermore, CA.

3. Hampel, Viktor E. and Jeffrey A. Schriebman. 1980. "A Personal System for Electronic Mail." M-115 (Draft), Rev. 1, Lawrence Livermore National Laboratory, Livermore, CA.

4. Kawin, Rick. 1980. "Seasonal Thermal Energy Storage Program On-Line Library System." Supplement No. 2 to M-0112 (Draft), Lawrence Livermore National Laboratory, Livermore, CA.

ENERGY STORAGE BIBLIOGRAPHY

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ABSTRACT

The status of the energy storage bibliography being prepared for the Office of Advanced Conservation Technologies of the Department of Energy is discussed. The approach was designed to minimize effort on the part of contributors and allow easy collection and annual updating of material. The proposed subject listings, indices, and citation format are presented, as is the method used to identify citations for inclusion. Documentation from 1975 to the present will be included in the bibliography.

INTRODUCTION

The Aerospace Corporation, in conjunction with the George Washington University, is compiling a bibliography of reports and other documentation developed for or by the former Energy Storage Division of the Department of Energy, currently operating within the Office of Advanced Conservation Technologies. The goals of the energy storage program are to develop and demonstrate, in cooperation with industry, energy storage systems that will increase the substitution of coal, nuclear, and solar energy for petroleum and natural gas and that will increase the efficiency of energy use and enable intermittent energy sources to provide continuous service in the industrial, utility, commercial, residential, and transportation sectors.

The major objectives of this bibliography, which will include documentation from 1975 to the present, are to preserve the historical background of energy storage activities (account of stewardship), assist in the transfer of technical information from the researchers and developers to the scientific and technical community, and provide a document that an interested public could easily obtain. It is anticipated that this document will be updated annually.

This paper presents the proposed bibliography content, organization, and format; the approach taken in developing the bibliography; and a summary of the current status and future activities.

BIBLIOGRAPHY CONTENT, ORGANIZATION, AND FORMAT

The bibliography has been tentatively organized as follows:

1. Introduction
2. Subject Listings
   - Electrochemical/Batteries (ECB)
   - Chemical/Hydrogen (CHY)
   - Magnetic (MA)
   - Mechanical/Flywheel (MEF)
   - Thermal (TH)
3. Indices
   - Authors
   - Organizations
   - Titles
   - Descriptors

The subject listings are based on the major elements within the energy storage program. Each of the citations will be placed in chronological order within the subject listing. The indices are presented by author, organization that performed the work, title of the citation, and descriptors. The latter are basically key words or phrases descriptive of the content of the document.

The proposed format for a typical citation is shown in Figure 1. All data relative to the subject document is incorporated into this citation. The format is designed so that the reader can scan the citation and readily locate the information desired. The abstract material in each citation is standardized. First the purpose is presented, followed by the major results. The approach used is presented in the methodology section.

It should be noted that each citation will be identified by an index number consisting of two parts. The letters identify the subject (e.g., TH is thermal), Index No. ECB-1

Title: Uniform Assessment Methodology for Energy Storage Applications

Author(s): Edwards, D.J.

Address and telephone number of first author:
The Aerospace Corporation
20030 Century Boulevard
Germantown, Maryland 20767
(301) 428-4752

Performing organization: The Aerospace Corporation

Sponsoring organization: Office of Advanced Conservation Technologies
U.S. Department of Energy

Publication date: December 1980

Document identification: Report 80-520

Nature of document: Detailed Presentation, System Analysis, Economic Analysis, Methodology

Abstract:

Purpose: The purpose of this report is to present a uniform methodology for the assessment of the technical and economic viability of energy storage in near-term solar applications. The objective is to develop a uniform methodology, input parameters, and a common expression for output perameters so that assessments of energy storage in solar energy systems can be directiy compared.

Result: The result of this report is a uniform methodology for the assessment of energy storage devices used in conjunction with solar energy conversion systems. A common analytic technique is presented, through which it will be possible to generate estimates of the value of energy storage systems in solar applications.

Methodology: The report addresses the technological range of parameters to be considered in further assessments, develops the governing assumptions for those assessments, and discusses both the system methodology and the economic methodology. The economic methodology develops figures of merit for further assessments for the homeowner, industry, and regulated utility sectors and for the Nation.

Additional information: Uniform assessment methodology is being used by the Brookhaven and Sandia National Laboratories and the Solar Energy Research Institute in the study "Solar Applications Analysis for Energy Storage."

Figure 1. Typical Citation Format

and the following number indicates the sequence within the subject listing. The citation is identified in all four indices by this same index number. Examples of the index formats are presented in Figure 2. All indices will be arranged in alphabetical order, listing index numbers that refer to the citation in the main subject file.

APPROACH

The approach taken in developing the bibliography is designed to minimize effort on the part of contributors and allow easy data collection and annual updating. The major steps are as follows:

- Current sources of energy storage bibliographic data were identified and reviewed, and an initial data base has been generated.

- A procedure is being implemented for modifying and verifying the initial data and incorporating new data.

- Printing and distribution plans are being discussed.

Identification of Citations

To identify appropriate citations for inclusion in the bibliography, various sources are being investigated by the George Washington University staff. These include appropriate data bases, other published bibliographies, journals, and Department of Energy and national laboratory personnel. One of the most lucrative sources was found to be the data base of the Department of Energy Technical Information Center at the Oak Ridge National Information Center. This data base was accessed by using the Department of Energy RECON system, an interactive online retrieval system. Using the "subject" thesaurus of RECON, the terms "energy storage," "hydrogen storage," "underground storage," and "electric batteries" were selected. They were then cross-indexed with "conservation," and 826 applicable citations going as far back as 1975 were identified.

Modification/Verification

To modify and verify past citations and to incorporate new ones, a questionnaire has been developed that will be sent to all first-listed authors. The format for this questionnaire is presented in Figure 3. For those citations that have already been identified, all available information will be incorporated, such as the title, author, etc. Additionally, as can be seen in Figure 3, if an abstract is already available, its source and the actual abstract will be incorporated as the last item on the questionnaire, providing all the pertinent information available is intended to facilitate the update.

A large amount of data is already on the TIC data base and has been captured on magnetic tape. Software has been developed by the Aerospace Corporation to properly reformat these citations.

AUTHORS

ORGANIZATIONS

TITLES

DESCRIPTORS

Figure 2. Examples of Index Formats

Title: Preliminary Development of the Band-Type Variable Inertia Flywheel (BVIF)

Author(s): Ullman, D.G.

Address and telephone number of senior author: ____________________

Performing organization: Sandia National Laboratories

Sponsoring organization: ____________________

Publication date: November 1979

Document identification: SAND-79-7089

Nature of document: please check as appropriate

Introduction, overview, or summary
Detailed presentation or examination
Feasibility study
Comparative analysis
System analysis
Economic analysis
Technical design
Systems summary
Administrative plan
Research plan
Case study
Conference proceedings
____
____

Abstract: (maximum 200 words total): ____________________

Purpose: ____________________

Result: ____________________

Methodology: ____________________

Additional information: ____________________

Abstract now on RECON: An energy storage flywheel with variable moment of inertia, combining the functions of energy storage and power control, is introduced and studied. The specific configuration addressed is the band-type variable inertia flywheel (BVIF). This hollow-shell flywheel is packed with long, thin bands of flexible material mounted like the mainspring of a watch. The performance equations of this configuration are derived and studied. A proof-of-concept model is described, and conclusions are drawn on the BVIF's operational potential.

Descriptors now on RECON: Design, Q1; experimental data, S; flywheel energy storage; flywheels, T1, D; graphs, D; mathematical models; performance, Q1, D; stress analysis; theoretical data, D.

Figure 3. Sample Format for Author Comment

Preparation for Printing and Distribution

Upon receipt of the verified and modified citations, the George Washington University will review each citation for format, consistency, and completeness. The citations then will be entered into a large-scale computer, and the main file and index files will be generated by the Aerospace Corporation. After the files have been generated, the output will be either GPO-compatible tape or camera-ready mats. Distribution plans for the final product are pending.

STATUS

The current status of the project is as follows:

- The content, organization, and citation format for the bibliography have been developed.
- Approximately 900 citations have been identified for inclusion to date.
- A questionnaire has been prepared for the authors to modify and verify past citations and to develop new ones.

The activities remaining include:

- Distributing questionnaires to the authors
- Quality control of the citations
- Entering the citations into a data base
- Generating main file(s) and index files
- Preparing a GPO-compatible tape or camera-ready mats

ASSESSMENT OF PORTFOLIO ANALYSIS METHODS FOR R&D PROGRAM MANAGEMENT

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ABSTRACT

The evaluation and selection of a balanced set of R&D projects directed towards primary energy objectives is a complex process. A number of portfolio analysis methods have been developed to assist in this process. In this assessment project, evaluations have been completed of several approaches including the Argonne/University of Chicago cost-benefit methodology, the University of Maryland Hierarchical Prioritization Model, and the Lehigh University Multi-Criteria Project Selection Model. These methods were evaluated in the context of a conceptual analytical system including information sources and analyses relevant to the selection of a R&D portfolio. Recommendations are presented regarding the use of these systems in support of R&D management along with other models and information sources involving regulatory factors, national policy objectives, and other criteria against which R&D projects may be evaluated.

INTRODUCTION

This study has been performed by MATHTECH, Inc., under the sponsorship of the National Center for Analysis of Energy Systems at Brookhaven National Laboratory, for the assessment of methods of portfolio analysis. The assessment deals with the potential for practical use of portfolio analysis methods for R&D planning and budgeting in the Office of Advanced Conservation Technologies of the U.S. Department of Energy and in its field laboratories. When the study was initiated, the primary interest of the project sponsors dealt with energy storage technologies. During the course of the study, the interests and responsibilities of the sponsor expanded to encompass a range of conservation technologies. Although the MATHTECH assessment dealt primarily with R&D program management of energy storage technologies, the discussions and some conclusions have been expanded where possible to deal with the broader range of energy conservation technologies.

The first step in the MATHTECH study was the specification of the objectives and content of R&D portfolio analysis, the identification of a conceptual analytical system, the information needs for such analysis, and criteria for the evaluation of alternative methods of analysis. The next step accomplished was the actual assessment and evaluation of a selected set of portfolio analysis methods in the context of the conceptual analytical system and assessment criteria that were established.

In the development and evaluation of portfolio analysis methods, it is essential to understand the real operating environment of the Office of Advanced Conservation Technologies, and its interactions with other offices in the Department of Energy, field laboratories, and the private sector which performs much of the development and is responsible for commercialization in markets. The research and development activities of the Office of Advanced Conservation Technologies cover a wide range of energy conservation and storage concepts. Quite often these conversion and storage concepts or devices are components of a larger energy conversion and delivery system such as a solar heating and cooling system for a building, an electric utility, or a transportation vehicle. This dictates the need for a high degree of understanding of the private sector activities and markets for the larger system in which the conversion or storage concept is to be used. Further, since R&D planning and management for the larger system may, in some instances, be the responsibility of another office of DOE, a high degree of internal coordination of planning and analysis is required.

The Department of Energy has utilized a formal Planning, Programming, and Budgeting System (PPBS) managed by the Office of Policy and Evaluation. PPBS guidance and objectives are established and individual programs were designed to be responsive to that guidance. The continued use of a formal planning system for overall DOE budgets, whether it involves PPBS or some other system, would dictate that program offices enhance their own R&D management systems. Further, the existence of some formal planning system can provide the impetus for the necessary coordination of analytical activities among different offices responsible for R&D management. Indeed, without this impetus for a high degree of coordination, it is unlikely that any single office could undertake the effort to develop and implement a practical and comprehensive R&D portfolio analysis methodology.

R&D PROGRAM MANAGEMENT - A CONCEPTUAL ANALYTICAL SYSTEM

Planning and analysis of research, development, and demonstration programs is a complex process covering a wide range of scientific and engineering disciplines, and of potential markets for components and systems which are successfully developed. Of prime importance in the planning and evaluation of R&D projects is consideration of the diversity of technical approaches and evaluation criteria that apply to the various stages in the research, development, and demonstration or commercialization cycle.

The research stage includes basic and applied research, as well as exploratory development. The objective at this stage is to prove the scientific feasibility of a new concept. Ideas for innovative technologies arise from the sciences and there is generally insufficient information to evaluate the market potential of the concept or even its possible role at this stage. In view of the need to encourage innovation, the research stage is usually funded on a level of effort basis with the primary criteria for funding involving the capability of the investigators and the overall importance of the area of scientific discipline (e.g. importance of catalyst or surface chemistry versus high energy physics).

As the research moves to the following stages of development and commercialization, the projects become better defined in terms of technical characteristics and potential markets. As the base of information expands, the ability to apply evaluation criteria related to the chances of success, the markets which will be affected, and the overall public benefits of the technology increase insignificantly. The objective of the development stage in the R&D cycle is to prove engineering feasibility and to begin to define the economic characteristics of the technology. Finally, the demonstration or commercialization phase in which the private sector becomes predominant serves to fully characterize the economic and commercial feasibility of the technology. This final stage normally involves very large investments and is subject to formal economic analysis of alternative projects. The need for government involvement in this phase must be evaluated in the light of private sector incentive.

The MATHTECH, Inc. evaluation focused on the planning and management process for research and development projects carried out by the Office of Advanced Conservation Technologies. This planning and management process involves such elements as:

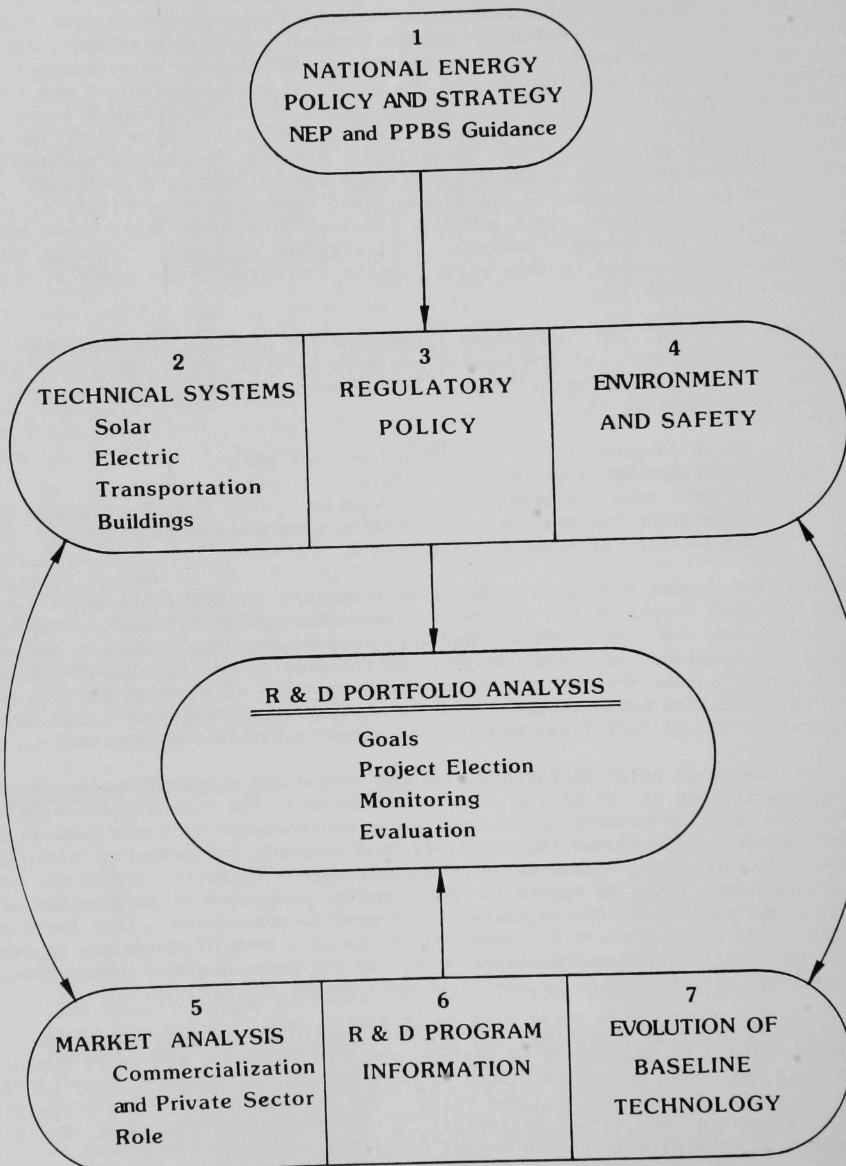
1. Establishment of R&D program and project goals.
2. Selection of programs and projects.
3. Budget level for programs and projects.
4. Monitoring and evaluation of ongoing programs and projects.
5. Termination of programs or projects.

Most of the formal portfolio analysis methods that are available require a very specific technical and economic characterization of the technology or project being evaluated. Thus, they appear to be most applicable at the level of comparing individual projects in the development and commercialization stage, rather than broad program areas or areas of basic research. They may be applied to broad program areas by dealing in a "bottom-up" fashion with the collection of individual projects or elements within the programs.

A number of relevant factors that are beyond the scope of analytical responsibilities of the Office of Advanced Conservation Technologies will affect the relative priorities, budget levels and decision criteria used in the development of a balanced R&D portfolio that properly reflects the role of government programs. These relevant factors may be organized around the major areas identified in Figure 1. Seven major categories of information are related to the R&D portfolio analysis and must be considered. In a large organization, such as the U.S. Department of Energy, each of these may be covered by a different organizational unit. In any case, whatever the source, this range of information is needed to make proper R&D decisions.

The methodologies evaluated to support portfolio analyses range from simple systems to quite complex systems requiring computer and staff support. Criteria that have been established by MATHTECH for the evaluation of portfolio analysis methods are outlined below. The categories A, B, and C apply to both judgemental and formal analytical portfolio analysis processes, while category D applies only to the formal analytical methods.

Figure 1: Conceptual System for R&D Portfolio Analysis



A. User Convenience

1. Extent and availability of data requirements and the existence or absence of a data base.

2. Transparency regarding assumptions and analytical method.

3. Ease of use by DOE staff and support laboratories.

4. Cost and level of staff support required to operate system.

5. Turnaround time for specific analyses.

B. User Relevance

1. Ability to incorporate judgemental information and to reflect the effects of uncertainties.

2. Degree of involvement of R&D manager.

3. Usefulness of output for project decision.

4. Usefulness of output for budget decisions.

5. Compatibility with PPBS (ability to incorporate user criteria for project selection).

C. Technical Content

1. Treatment of storage and conservation options.

2. Description of technical system,e.g., building, utility grid, etc. in which technology will be deployed.

3. Consideration of system level impacts.

4. Consideration of public costs and benefits in addition to private sector incentives.

5. Consideration of regulatory interactions.

6. Environmental and safety issues.

7. Ability to deal with other required information:

- National policies and strategies.

- Private sector market condition and commercialization incentives/ disincentives.

- R&D program information and estimates of likelihood of success.

D. Methodology Content

(Applies to the formal portfolio analysis methods only.)

1. Ability to handle diverse criteria for program/project.

2. Consistency of the problem statement with the goals of the R&D manager, and validity of the assumptions made.

3. Validity of the relationships between the endogenous and exogenous variables and of any functional forms assumed.

4. Appropriateness and accuracy of the analytical tools used in the methodology.

5. Validity of the algorithmic process used to translate the methodology into a usable model.

6. Assessment of the sensitivity of the methodology to a changing operation environment.

7. Assessment of the predictive validity and plausibility of the model by an analysis of the case studies to which the methodology was applied.

8. Documentation and peer review of the analytical system.

CONCLUSIONS AND RECOMMENDATIONS

The development, implementation, and maintenance of an operational portfolio analysis method by the Technical and Economic Analysis Program of the Office of Advanced Conservation Technologies represents a significant commitment of both staff and budgetary resources. Any comparison of alternate approaches must include the option of foregoing any formal analytical method. The assessment of which method, if any, is most appropriate must be based on the specific planning needs and capabilities of the Office of Advanced Conservation Technologies, as well as the planning and evaluation methods used in the Office of Conservation and Solar Applications, and in the Office of Policy, Planning, and Analysis. Taking these factors into consideration, along with the past implementation within DOE of a formal Planning, Programming, and Budgeting System (PPBS), we conclude that a formal and standardized portfolio analysis method should be implemented in the Technical and Economic Analysis Program. At the time of this writing, it is not clear whether PPBS or a similar formal system will be maintained in DOE. Our recommendations are contingent on the continuation of a formal system, since there must be a high degree of interaction between the Technical and Economic Analysis Program and other offices. It is likely that the necessary degree of cooperation will exist only under the impetus of a formal DOE-wide planning system. Our recommendation that a formal portfolio analysis be implemented is heavily influenced by the nature of energy storage and conservation technologies as critical components of a wide variety of energy conversion and utilization systems.

The portfolio analysis process may be thought of as a three-step process along the following lines:

Step 1. Development of criteria for ranking of R&D projects. Examples of ranking criteria now employed are as follows:

- Oil and gas savings (PPBS Objective)
- Commercial potential (PPBS Objective)
- Environmental, social, and institutional impacts (PPBS Objective)
- Need for Federal program (PPBS Objective)
- Project benefit/cost ratio
- Energy savings potential

- Probability of technical success
- End use applicability

Step 2. Analysis of impact of program or project against criteria for R&D program selection, and

Step 3. Integration of scoring and impact information into project ranking for selection.

The relationship of the portfolio analysis methods and supporting techniques reviewed in this study to this overall process are quite clear. The Argonne-University of Chicago benefit/cost methodology provides the basic structure for representing and comparing alternative projects in terms of a number of quantitative program evaluation criteria; thus, this work supports the critical second step of the process. The Lehigh work consists of two activities, the development of group techniques for arriving at subjective estimates and impacts (Step 2) and the application of a Multi-Criteria Project Selection Model to the integration of scoring estimates under budget constraints to arrive at an overall ranking, or portfolio, of R&D projects (Step 3). The University of Maryland Hierarchical Prioritization Model is applicable to Step 3, while their techniques for estimating probability of success for an R&D project are applicable to Step 2 of the portfolio analysis process.

The ability to accurately reflect the key technical and economic parameters for competing technologies and projects on a consistent basis is a central issue in the design and selection of portfolio analysis methods. The need to introduce critical parameters into the process essentially forces the use of formal analytical methods. This same requirement also leads to extensive data requirements that can be the ultimate constraint on the practical implementation of the system. Some compromise is necessary on data issues to ensure that critical parameters and relationships are captured while not attempting to incorporate too much detail. This is the essential art of analysis. The ANL-University of Chicago benefit/cost methodology is the portion of the portfolio analysis system that deals with technical information on storage options. At the present stage of development, storage options are dealt with in the building and utilities sectors. The current plan is to develop additional technology modules for the transportation and industrial sectors. Conceptually, the modules could also be extended to incorporate a number of energy conservation options. The major deficiency in technical content is that system level impacts due to changes in load characteristics of end use devices in buildings (e.g. impacts of customer space heat storage on utility load curve and generating mix) are not now incorporated and no plan was evident to address this issue. This deficiency also makes it difficult to estimate the effects of regulation on the viability of end use R&D projects. The overall evaluation of the ability of portfolio analysis methods to incorporate specific technical details is summarized in Figure 2.

As is evident in the summary presented in Figure 2, the technical characteristics of major storage technologies for building and utility applications are already included in the ANL-University of Chicago system. Work is in progress or planned on other storage technology modules for other market applications such as transportation and industry. The methods also can incorporate market penetration algorithms (ANL) and pertinent information on R&D progress (ANL and University of Maryland). Budget limits may be factored into the portfolio analysis process using the Multi-Criteria Project

FIGURE 2: SUMMARY EVALUATION OF TECHNICAL CONTENT OF PORTFOLIO ANALYSIS METHODS

TECHNICAL FEATURE	EVALUATION OF STATUS
1. Technical and economic characteristics	
- Storage	I (ANL)
- Conservation	F
2. Description of technical system in which technology will be employed	I or C depending on sector
3. System level impacts	I or C depending on sector
4. Regulatory effects	C
5. Environmental and safety issues	C
6. Other information	
- National policy objectives	C or F
- Market penetration	I (ANL)
- R&D program information (progress and estimates of probability of success)	I(ANL, U.of Md.)
- Budget limits	I(Lehigh, U.of Md.)

Legend: I - Included at this time.

F - Not now included, but can feasibly be added to present structure.

C - Not now included, but can be introduced by using other models or data sources.

X - Not now included, but extremely difficult to add to system.

Selection Model developed by Lehigh. Budget limits may also be introduced into the University of Maryland Hierarchical Prioritization Model, but with considerable difficulty.

The end-use market orientation and the modular structure of the ANL-University of Chicago system allows for the extension of the method to cover a wide range of alternative conservation technologies; thus it noted that while this feature is not now in the system, it is feasible to add those additional technologies to the structure.

It is apparent that the major deficiencies of the system as it now exists are the inability to deal with many of the larger system-level impacts associated with changes in end use devices, interactions with regulatory issues, choices between supply-oriented technologies and end use technologies, and other national policy objectives. These deficiencies are understandable in view of the need to focus the effort on specific technologies and markets pertinent to energy storage. It is true, however, that both storage and conservation technologies are generally components of larger systems and the interactions with other systems are important. As an example, the widespread use of customer-side-of-the-meter storage of electricity or thermal energy will affect the load curve, and therefore, the market for central station load leveling systems. Regulatory policies such as marginal cost or time-of-day pricing will in turn affect both of these markets. Such interactions are of vital importance to the assessment of projects and must be included in some manner. Fortunately, there are a large number of system level models available that are probably compatable with a portfolio analysis system. Thus, the problem is not one of building a single, larger scale model, but is one of allowing for the flow of relevant information to the portfolio analysis system from these more complete energy system models.

Our basic conclusions and recommendations may be summarized as follows:

1. A formal and standardized portfolio analysis method should be developed and implemented within the Office of Advanced Conservation Technologies in order to deal properly with the complexities of markets for energy storage and conservation technologies and to relate Office plans to overall objectives as represented in such formal planning mechanisms as the Planning, Programming, and Budgeting (PPB) system.

2. It is judged to be feasible to assemble the basic components of a portfolio analysis system drawing upon existing analytical methods and informaion sources. A basic system could be assembled from among the projects reviewed here, augmented with improved information and selected special topical analyses from the Energy Information System, within the FY 1980 staffing and budget levels of the Technical and Economic Analysis Subprogram.

3. The portfolio analysis method must be operationally simple but must deal with the essential DOE objectives defined by the Secretary's Office. The need to keep the system operationally simple requires that allowance be made to utilize external information sources as well as judgement when other information is either not available or not relevant to the problem at hand.

4. Of the candidate systems that were reviewed in this study, the Argonne-University of Chicago cost/benefit method comes closest to providing the level of project-specific detail necessary to meet the needs of the Office of Advanced Conservation Technologies. Its modular structure is compatible with the needs to address a variety of technologies. The approach also allows for the introduction of information based on judgement and other analyses.

5. While some of the information needs can be filled by initiating complementary study projects within the Technical and Economic Analysis Program, the range of storage and conservation applications and the extent of regulatory and economic impacts on these technologies dictates that much of the information needed for portfolio analysis must come from external sources, including program managers, the Office of Policy, Planning and Analysis, and the Energy Information Administration.

6. Uniform methods should be developed to estimate the timing and cost of R&D programs and their likelihood of success. Much of this information can be assembled by program managers; however, some peer review process will be necessary to protect from biases.

7. Information on overall priorities, objectives, and other measures by which the effectiveness of storage and conservation programs may be guaged can be provided by the Office of Policy, Planning and Analysis in the Policy and Fiscal Guidance document prepared under the PPBS or similar planning system.

8. System level impacts are critical to the evaluation of energy storage technologies. In the electric utility sector, for example, it is important to know how storage and conservation might lead to changes in the overall load curve affecting the generating mix, beyond the simple displacement of peaking units. There are also potential system level impacts of some significance in building and transportation applications of energy storage. At present the best capability in DOE for estimating such system level impacts is the Office of Applied Analysis in the Energy Information Administration. A well-designed analysis could provide some basic system level impact information that could be used in a portfolio analysis system.

9. Further work on portfolio analysis methods should be coordinated and focused on operation planning and budget needs of the Office Staff. This coordination can be achieved through live demonstrations and workshops.

A summary evaluation of the content of the portfolio methods that were reviewed, relative to the endurance criteria, is presented in Figure 2.

BIBLIOGRAPHY

1. P. Nanda and K.C. Hoffman, "Conceptual R&D Analysis Systems - The Context and Criteria for R&D Portfolio Analysis."

2. Feller, K.G., et al., "A Review of Methods for Evaluating R&D," ICID - 18890, prepared for U.S. Department of Energy, Office of Applied Conservation

Technologies, November 14, 1980.

3. R&D Evaluation System, Argonne National Laboratory and University of Chicago, October 1980.

4. J.M. Hihn, "A Hierarchical Approach to Decision Making: Economic Theory and Methodology," Ph.D. dissertation, University of Maryland.

5. Wilson, "Multiple Criteria Project Selection Module: Zero-One Interger Goal Programming with Sensitivity Features," Leigh University Technical Report, October 1980.

6. Energy Research and Development Administration, A National Plan for Energy Research, Development, and Demonstration, ERDA-48, June 28, 1975.

7. Energy Research and Development Administration, A National Plan for Energy Research, Development, and Demonstration, ERDA 76-1, April 15, 1976.

8. International Energy Agency, A Group Strategy for Energy Research Development and Demonstration, OECD, Paris, 1980.

RD&D EVALUATION SYSTEM

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ABSTRACT

The RD&D Evaluation System is a computer-based, interactive analysis system for evaluation of DOE programs. The model is intended to facilitate rapid, frequent evaluation of alternative storage applications and technologies and has been used by DOE in its Program Planning and Budgeting System (PPBS) process. The System embodies a modular, technology-oriented, benefit/cost approach to RD&D evaluation. The system is supported by technology, price, and market data bases each of which is independently accessible, consistent and easy to use. For each technology, benefits associated with reductions in resource (energy, capital, labor, etc.) use relative to the respective baseline technology are calculated. Results are region specific and include adjustments for social costs. A present value technique is used to consistently include future costs and benefits associated with each technology. Technological uncertainty is handled explicitly through program manager inputs; market penetration algorithms are tailored to each application area.

INTRODUCTION

Research and development is an investment activity with returns and costs subject to the same evaluation principles as other investments. The fact that returns are more difficult to measure than for many types of returns has been an impediment to bringing the tools of economics to bear on the analysis of research and development. Considerations of risk are involved both in the probability of success in developing new technologies from a given type of research and development and the probability that a technology, if developed, will use less resources to produce a given output than existing technologies. The difficulties of evaluating research and development are increased by the need to combine concepts from economics with knowledge from the engineering and physical sciences.

Research and development involves interactions between public and private decision making that have been of long standing concern but have been insufficiently studied. Determining which technologies will be competitive and eventually enter the market place is, to a significant level, at the heart of private sector decision-making. Maximizing return on investment is one of the primary objectives. Without government intervention, energy-conserving technologies will enter the market when they yield rates of return higher than existing technologies. This may be due to rising alternative fuel prices, decreasing production costs, or improved efficiencies because of technological breakthroughs. Under these conditions, private sector firms may realize sufficient benefits in terms of a forecasted time stream or revenues to justify the investment in RD&D costs.

There may be several reasons for wishing to accelerate this process:

1. Significant benefits may exist for society in terms of spillover effects that cannot be captured by the individual firm;

2. The individual firm may be unwilling or unable to sell high-risk or long-term RD&D programs in private capital markets;

3. Insurance against certain risks may be desirable for society to protect against unpredictable short-run shortages (embargo, war) or disruptive price adjustments.

Sharing the RD&D costs and hence accelerating the time from conception to commercial availability of new energy conserving technologies is one way to capture benefits earlier and achieve public objectives.

As an investment of limited resources, scrutiny in an economic context can provide useful insight. This is not to limit discussion to such obviously economic measures as dollars and cents, but to provide a framework for deciding how to obtain the highest return, measured in the broadest sense, on public investment.

In the energy field, where large commitments are being made, the need for effective evaluation procedures is particlarly great. The work outlined here extends and enriches current evaluation procedures through the combined contributions of the University of Chicago, Argonne National Laboratory, and its subcontractors. This has provided a methodology for evaluating RD&D investment strategies, improving data for use within this framework, and involving those familiar with the technologies in the planning process.

RD&D EVALUATION SYSTEM OVERVIEW

The RD&D Evaluation System is a computer-based, interactive analysis system for evaluation of DOE programs. The model is intended to facilitate rapid, frequent evaluation of alternative storage applications and technologies. The system can be used to evaluate a new storage concept or to establish program goals for an existing program. The program manager solicits cost/performance data concerning the new concept. These data are submitted to the model, which provides a comparative analysis of the new technology for a selected application area. The model calculates the cost of providing a given service (e.g., space conditioning, transportation), estimates market penetration and associated energy savings/shifts, and net benefits. This information, together with additional outside expert evaluation assists the program manager in making a funding decision.

The system has been used to assist DOE in evaluating alternative program plans in the context of the Program Planning and Budgeting System (PPBS). Figure 1 illustrates this application. In this case, the DOE program manager provides the projected technology cost/performance data for each alternative budget. Changes in projections of benefits and costs and associated energy savings/shifts for each technology can help to redefine program emphasis and direction, establish new program goals, and develop a budget submission.

ANALYSIS APPROACH An overview of the system structure is provided in Figure 2. The system embodies a modular, technology-oriented, benefit/cost approach to RD&D evaluation. The system is supported by technology, price, and market data bases each of which is independently accessible, consistent, and easy to update.

For each technology, the program calculates benefits associated with that technology based on reductions in resource use (energy, capital, labor, etc.) relative to the respective baseline for social costs (value of oil imports, tax effects, environmental effects, etc.). These benefits can then be compared with the associated RD&D costs, both public and private. A present value technique is used to consistently include all future costs and benefits associated with each technology. In addition, quantification of technological uncertainty is handled explicitly through program manager supplied inputs.

STORAGE APPLICATION AREAS The rate and extent of market penetration are critical variables affecting the estimated benefits of each technology. Market penetration is in turn a function of the benefits of each new storage technology relative to the corresponding baseline technology. Finally, the market penetration calculations must be tailored to the unique characteristics of each market. For these reasons, each storage technology has been classified into one of four application areas:

- Residential/Commercial Space Conditioning
- Electricity Production
- Transportation
- Industrial

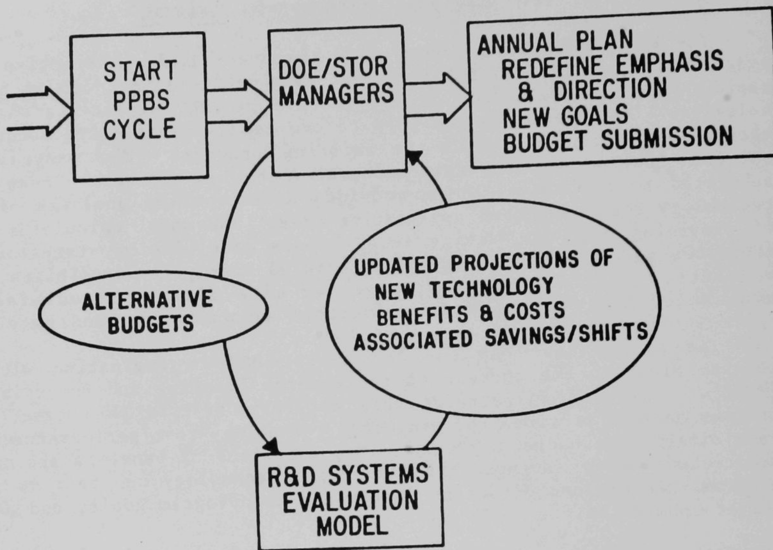

Fig. 1. Use of R&D Systems Evaluation Model for PPBS Budgeting

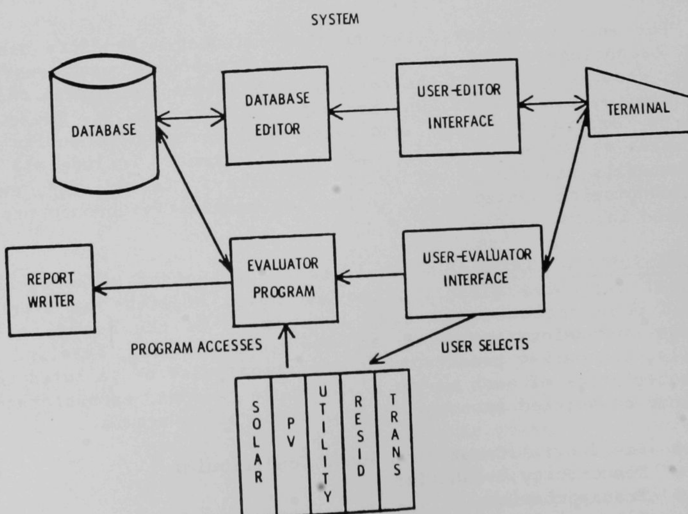

Fig. 2. System Overview

Individual storage technologies are grouped according to application area in Figure 3.

SYSTEM DEVELOPMENT TASKS

In order to develop a complete analytic capability for all storage technologies and be able to provide comprehensive and timely results, a phased approach to system development has been adopted. Phase I represents a first cut analysis. Simplified algorithms for technology characterization and market penetration have been developed for all storage technologies. Combined with national market data bases, the Phase I analysis has been used to estimate the benefits attributable to each storage technology for three "snapshot" years --1985, 1990, and 2000. During subsequent phases of system development a complete analytic capability is being developed, technology by technology, for all storage technologies. A more detailed discussion of this advanced system development follows.

TECHNOLOGY MODULES A separate technology module is being developed for each storage technology application listed in Figure 3. The cost of providing a given service for each application is a function of not only the device cost/performance variables, but also of regional variables, such as weather. The time period (i.e., 1980 vs. 2000) can also affect the cost of providing each service mainly due to changes in fuel prices. Therefore, regional calculations are performed for eight five-year time periods from 1980-85 to 2015-20.

The basic functional format for each technology module is illustrated in Figure 4. Beginning with input cost/performance data and interactive input from the program manager, the probability of technological success is calculated. This is used to generate three (low, mean, high) sets of cost/performance data which are used to calculate life-cycle costs for providing each unit of service within the selected application area. These life-cycle costs together with the comparable baseline technology life-cycle costs enable prediction of market penetration. Finally, net benefits (private and social) and savings are calculated for each region and time period.

At the heart of each technology module is the simulation of the key cost and performance trade-offs for a given application. This feature ensures realism and permits the use of the module for performing sensitivity analyses. For example, in simulating electric vehicles the battery model includes:

- Specific energy vs. average power,
- Specific power vs. specific energy,
- Battery cost as a function of total energy and power,
- Battery scale effects, and
- Specific power and battery lifetime as a function of depth of discharge.

SYSTEM APPLICATIONS

- RESIDENTIAL/COMMERCIAL SPACE CONDITIONING
  - TES HEATING†
  - TES COOLING†
  - TES DOMESTIC WATER†
  - ACTIVE SOLAR/TES†
  - PASSIVE SOLAR/TES†
  - AQUIFER STORAGE*
  - CHEMICAL HEAT PUMPS*
- ELECTRICITY PRODUCTION (CENTRAL/DISPERSED)
  - UTILITY STORAGE†
  - SOLAR/STORAGE*
  - WIND/STORAGE*
  - OTHER ADVANCED CONCEPTS/STORAGE*
- TRANSPORTATION
  - ELECTRIC VEHICLES†
  - HYBRID VEHICLES*
- INDUSTRIAL
  - ELECTROCHEMICAL PROCESSES*
  - HYDROGEN PRODUCTION*
  - WASTE HEAT/TES*
  - WASTE HEAT/AQUIFER*

* Phase I Development
† Advanced Development

Fig. 3. Storage Technology Application Areas

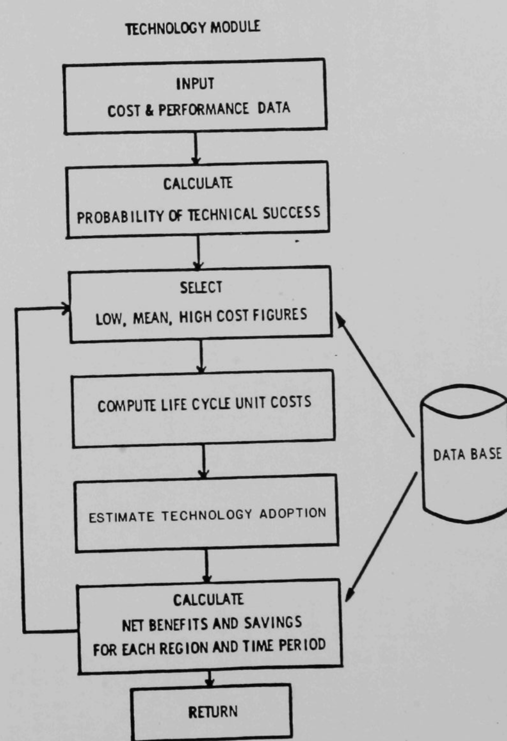

Fig. 4. Technology Module Flow Chart

Subject to the above design constraints, vehicle design is optimized to minimize life-cycle costs associated with a given vehicle mission as defined by:

- Minimum power requirements,
- Payload capability, and
- Probability distribution of daily trip lengths.

PROBABILITY OF TECHNICAL SUCCESS The probability of technical success module takes user supplied assessments of new technology performance and converts this information into quantitative probability statements. The module was designed for minimal input information requirements.

In order for the routine to have general applications, all questions are phrased in terms of best and worst case conditions. Thus, a cost parameter would have a worst case of high dollar cost while the worst case for a battery discharge efficiency parameter might be a low value. Next, the user is requested to give his estimation of the probability that the realized value for the parameter will be better than the DOE program goal. In a similar fashion, the user is requested to give his opinion as to the probability that the realized value for the parameter will be better than a program supplied reference value.

The choice of the probability benchmarks are purely arbitrary. The DOE program goal is used simply because it is a familiar number to the project manager and, therefore, it might be easier to decide upon an appropriate probability for this benchmark.

MARKET PENETRATION The current version of market penetration is based upon a segregation of the national market into geographical and technological submarkets. A least-cost adoption criterion is used for each submarket on a period-by-period basis. These results are aggregated to obtain a national market penetration curve.

An improved formulation of market penetration based upon a dynamic, competitive market model incorporating consumer preference behavior is currently being developed. The functional form is given by the following relation:

$$M_i(C_C, C_N, t) = \alpha * g(C_C, C_N) * S(t) \tag{1}$$

where

$M_i(C_C, C_N, t)$ represents the market fraction for the new technology in submarket i for time period t;

α represents a substitution index which measures the relative quality of services supplied by the new technology relative to the conventional technology;

$g(C_C, C_N)$ specifies the level of ultimate market penetrations as a function of life cycle costs C_N and C_C for the new conventional technologies respectively; and

S(t) represents the fraction of ultimate market penetration achieved t years after introduction of the new technology.

Historical data on previous adoption of technological innovation is being used to estimate the functional form of g and s.

SUPPORTING DATA BASES The data bases which support the RD&D evaluation system can be functionally divided into two categories -- technology-specific cost and performance data and market data. The technology cost and performance data bases characterize current and future technologies against which storage technologies must compete and provide the basis for the competitive evaluation of storage technologies and their associated benefits. These data bases reside within each technology module and are user accessible during the evaluation process.

The market data base contains most of the information used by the various technology moduels to characterize markets out to the year 2020. The data base is easily accessible to the user and individual or groups of data can be retrieved and updated within the system. The data base elements include data on housing stock and heating system characteristics for the largest 65 Standard Metropolitan Statistical Areas (SMSA) and rural areas of each state, transportation sector data for 158 urbanized areas, regional weather and fuel price data, and fuel-mix and demand projecting for the nine National Electric Reliability Councils (NERC) regions. The data base is also being extended to include projections for commercial buildings.

PORTFOLIO ANALYSIS The interactions among projects during the RD&D process and in the market place must be taken into account in order to maximize the return of the total RD&D effort. Projects can be related during the RD&D phase because the research effort spent on one project produces knowledge that can be applied to another project. A relation between projects in the market place can arise because the success of one technology can increase or decrease the demand for another technology and thereby affect the benefits received from the two projects.

The presence of these dependencies requires that projects be analyzed as a group rather than independently. The portfolio model accounts for these interrelationships by the development of a selection criteria for choosing the component projects which collectively yield the greatest benefit for a given RD&D outlay.

Because the model requires at least some information on the probability of technical success and knowledge of the possible interdependencies between projects, the portfolio model may not always be appropriate as a first step in the funding process. Therefore, to maintain the model as a realistic tool for the evaluation of project funding, we delineate a general time sequence, indicating the points at which the portfolio model may be used.

RESULTS AND CONCLUSIONS

Although the RD&D Evaluation System is still being developed, the current system has been successfully used to assist DOE in performing numerous analyses. This section summarizes two such analyses.

In order to assist the DOE task force on "Distributed Thermal Energy Storage in the Residential Sector: Commercialization Readiness Assessment and Implementation Strategy," the system has been used to perform a regional benefits analysis. This analysis showed that by the year 2000 total sales of TES space heating units of 4.5 million units and representing an aggregate charging capacity of 100 GWe were feasible. The resulting benefits were annual and cumulative oil/natural gas savings of 80 and 700 million barrels of oil equivalent respectively and a total discounted customer cost savings of 14 billion dollars. These oil and natural gas savings were primarily a result of substitution of off-peak electricity for direct combustion of oil and gas in the end-use sector. Finally, the regional analysis indicated that these benefits were primarily concentrated in the rural areas of DOE Regions 4 and 5.

The system has also been used to quantify energy savings and shifting for each storage technology. A recent analysis performed for use by DOE in the PPBS cycle has estimated total annual oil and natural gas savings and net energy savings for the years 1985, 1990, and 2000 for three cases: market saturation, continued DOE program, and no DOE program. With continuation of the DOE program, total oil and natural gas savings for the year 2000 have been estimated at 2.8 quads. These estimates represent approximately seven percent of the potential savings attainable under complete market saturation conditions. With no DOE program, the savings are approximately 20% of the with-DOE savings case.

These two examples illustrate how the RD&D Evaluation System has been used. Other potential system uses include: establishment of RD&D program goals through sensitivity analyses, determination of the need for more detailed system analyses and data requirements, and quantitative data inputs for use in future portfolio analyses.

CHAIRMAN'S SUMMARY OF PANEL DISCUSSION

SESSION II
INFORMATION MANAGEMENT AND R&D EVALUATION

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The discussion and questions focused exclusively on the presentations regarding R&D project evaluation and portfolio analysis. In fact, the discussion was concerned with the usefulness and applicability of explicit R&D project evaluation techniques in general and only one question addressed one of the specific techniques discussed. Broadly speaking, four questions were asked:

1. Assuming a changing emphasis in the current administration toward funding relatively more basic research, are explicit evaluation techniques and portfolio models still useful?

2. Is there any practical way to test portfolio evaluation techniques against historical experience?

3. Although portfolio analysis might be useful in sorting out "big-picture" issues among generic technologies, is it really potentially useful for distinguishing among particular technologies?

4. What is the importance of various portfolio interactions and how does the Argonne National Laboratory/University of Chicago (ANL/UC) approach treat these interactions?

The following paragraphs summarize my understanding of the responses to these questions.

It was agreed that evaluation of R&D projects with long-term pay-offs is considerably more difficult than evaluating projects with short-term pay-offs. It is not only difficult to quantify the uncertainty in the technology's cost and performance, but sometimes it is difficult to specify even the markets that might be relevant for the technology. However, it was agreed that explicit evaluation techniques still have an important role to play in understanding long-term possibilities. The discipline of going through a logical and explicit process insures that whatever information is available will be used. For example, the evaluation techniques can quite often be used to generate insights rather than to generate final bottom-lines that are dogmatically accepted one way or another. Most evaluation techniques can be utilized to answer "what if?" questions. If an advanced technology met 50% of its performance goals, what impact would it have in the market? As another example, the evaluation techniques can usually be used to back out answers to questions like what minimum performance goals must be met for a particular technology to make a market penetration of 20%? Several panel members agreed that such analyses, even if they were not performed as part of one, unified bottom-line portfolio analysis, could still save a large portion of the federal energy R&D budget.

Retrospective testing of portfolio evaluation techniques was generally agreed to be impractical. Since the R&D process as a whole involves many interacting parties both in the public and private sector, a retrospective test would require reconstruction not only of the options faced by each party but also the information held by each party, and the relationships among the parties. Obviously, such a reconstruction is impractical, if not impossible. Our effort would be much better spent trying to understand such factors as they pertain to present and future decisions.

In response to the question of whether portfolio analysis could address trade-offs between specific technologies as well as answer big-picture questions, the panel agreed that, if used appropriately, such techniques could be used at any level of detail.

The importance of accounting for portfolio interactions in evaluating R&D projects was stressed by members of the audience and agreed to by the panel. Examples of such phenomena are numerous, the most basic being the competition among projects for scarce resources. Another example is when a technology has a value as a hedging or backstop alternative. Although such a technology might not appear to be valuable when evaluated in isolation, its value will be evident when it is considered as a hedge in the event of the failure of the preferred technology. A final example of the implications of portfolio interactions is the fact that the value of technologies that compete for the same market niche can be significantly overestimated if this competition is not considered. At this point in time the ANL/UC approach is being used primarily on a project by project basis so that portfolio interactions are not a central concern. However, the intention is to consider some of the portfolio effects as the approach evolves and as demand for more detailed portfolio analyses materializes.

The discussion summarized above focuses on technical questions relating to the applicability and usefulness of the techniques discussed. However, a theme that recurred in the discussion was that the applicability and usefulness of explicit R&D project or portfolio evaluation techniques at DOE depends more on organizational commitment than technical questions. Until the organization faces the reality that resources are, and will continue to be, constrained and makes a commitment to systematic planning, there is no incentive to use R&D project or portfolio evaluation techniques. In fact, an office that performs careful evaluations of its programs and projects is putting itself at a disadvantage. Its relatively unattractive projects will immediately be given tough scrutiny and perhaps eliminated in favor of even less attractive projects from another office that are not subjected to a similar, careful evaluation. R&D project evaluation techniques will be useful only when DOE moves from the era of trying to throw money at everything that "looks good" to making the tough trade-offs faced by an agency with limited resources.

SESSION III:
STORAGE FOR LOAD MANAGEMENT

DISPERSED ENERGY STORAGE ANALYSIS

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ABSTRACT

An analysis of the steady state and operational performance of a number of residential space heating and cooling thermal energy storage (TES) systems is being conducted. The primary objective of these efforts is to identify those TES systems that are most suitable for specific climatic regions under an imposed time-of-day (TOD) electric rate structure. This determination will be based primarily on energy use characteristics and annualized system life cycle cost. A corollary objective is to compare the technical and economic performance of these TES systems with alternative conventional systems. These comparisons will be completed by considering various technical and economic parameters that are projected to have a significant influence upon the performance and cost effectiveness of each system.

An hourly simulation of the operation of each system which accepts system steady state performance data, building thermal loads, and a description of the electric rate structure will be utilized to project annual energy use required to meet the thermal load of a typical residence in each climatic region. The output of this analysis allows for the determination of energy costs associated with the operation of each system which is then used in conjunction with system capital costs to compute system life cycle cost.

TECHNICAL APPROACH

The general approach being utilized consists of five primary activities. The first of these involves computing hourly building thermal loads for typical residences at Boston, MA; Miami, FL; and Nashville, TN. In parallel with this effort, steady state performance characteristics have been defined for each system based on manufacturer's data, empirical information or by computer simulation. The results of these two activities will then be combined, through a control algorithm, with hourly meteorological data and a description of an imposed electric utility rate structure to determine energy use on a hourly basis for an entire year. System capital cost along with energy costs associated with the operation of the system are then put in to a life cycle cost algorithm which is used to determine the total cost of ownership of each system. Comparisons between systems will then be made based on these economic and technical results.

SYSTEM DEFINITION

Tables 1 and 2 identify the thermal storage systems considered in the analysis. Each of the latent heat systems include a TES subsystem that has been retrofit to either a conventional air conditioner or heat pump system. Systems L1-L6 are conceptual designs that have been developed by RTI for the purpose of this study. Each of these six systems charge storage by allowing the subsystem to act as one of the two primary heat pump heat exchangers while simultaneously acting as a storage vessel. This, of course, necessitates that a refrigerant to storage material heat transfer process takesplace.

For those systems providing for storage heating the subsystem acts as the condenser of the cycle while for cooling storage systems the storage vessel is the evaporator and, therefore, causes the storage material to be solidified during charging. These six systems are further characterized by the heat transfer mechanism used to discharge the subsystem. Direct systems discharge to the indoor space by circulating indoor return air through the subsystem thereby heating or cooling the air stream to provide for space conditioning. Indirect systems, on the other hand, are discharged by again allowing the subsystem to act as one of the two required heat exchangers of the heat pump cycle. Therefore, during indirect discharge of a system providing for storage heating the subsystem would act as the evaporator of the cycle and a cooling storage system would require the subsystem to act as the condenser during discharge.

An advantage of the indirect systems is that the heat pump cycle would be seeing a relatively (as compared to the ambient) high temperature source or low temperature sink thereby increasing the instantaneous system coefficient of performance (COP) over the conventional system operating at the same time. Another advantage to these types of systems is that the subsystem is a more effective heat exchanger than the conventional air-to-refrigerant heat exchanger, thereby decreasing the heat exchanger temperature difference for the same source or sink conditions which also results in a more efficient system. On the other hand, compressor operation during the on-peak period, as required by the indirect systems during discharge, results in a relatively high power demand compared to the operation of only a fan, for example.

Systems L7 and L8 are ice storage systems that are similar in conceptual design to commercially available systems. These systems function as does L3 during charging but make use of an intermediate chilled water loop between the subsystem and an indoor chilled water coil to effect discharge.

The last two latent heat systems, L9 and L10, are similar in concept to the Chub systems developed at the University of Delaware. These systems are charged by placing the subsystem downstream of the conventional indoor coil and circulating the heated or cooled air exiting this heat exchanger

Table 1. Latent Heat Systems

System No.	Heating Mode Charging/Discharging	Cooling Mode Charging/Discharging	Storage Temp.
L1	Indirect[c]/Direct[b]	Heat Pump[a]	114°F
L2	Indirect/Indirect	Heat Pump	81°F
L3	Heat Pump	Indirect/Direct	32°F
L4	Heat Pump	Indirect/Indirect	55°F
L5	Indirect/Indirect	Indirect/Direct	45°F
L6	Indirect/Indirect	Indirect/Indirect	55°F
L7	Fossil	Indirect/water loop[d]	32°F
L8	Heat Pump	Indirect/water loop	32°F
L9	Heat Pump	Chub Direct/Direct	55°F
L10	Chub Direct/Direct	Heat Pump	90°F

[a] Non-storage mode
[b] Air/storage material heat transfer
[c] Refrigerant storage material heat transfer
[d] Air/storage material heat transfer within an auxiliary water-to-air heat exchanger

Table 2. Sensible Heat Systems

System No.	Heating Mode Charging/Discharging	Cooling Mode Charging/Discharging	Storage Temp.
S1	Electric pressurized hot water/Water loop[d]	Air conditioner[a]	290°F
S2	Electric hot brick/ Direct	Air conditionr	1500°F
S3	Electric unpressurized hot water/Water loop[d]	Air conditioner	200°F
S4	Heat Pump Water Loop[c]/ Water Loop	Heat Pump Water Loop/ Water Loop	N/A
S5	Domestic Hot Water		--

[a] Non-storage mode
[b] Air/storage material heat transfer
[c] Refrigerant storage material heat transfer
[d] Air/storage material heat transfer within an auxiliary water-to-air heat exchanger

through the subsystem. The Chub systems are discharged in the same manner as the direct Systems L1 and L3.

Four sensible heat space heating and cooling systems are being considered along with a single domestic hot water storage system. System S1 is a pressured hot water system that is charged by immersion-type electric resistance heaters and discharged by circulating the resulting heated water through an indoor water-to-air heat exchanger. Space cooling is provided using a conventional vapor compression air conditioner. System S3 is similar to S1 except the storage vessel is unpressurized and, therefore, stores energy at a lower temperature level.

System S2 is a ceramic storage system that uses resistance heaters to add sensible heat to a mass of ceramic bricks. Indoor return air is then circulated through air passages between the bricks and heated to provide for space conditioning during discharge operation.

A heat pump coupled hydronic sensible heat system is provided for by System S4. This system is charged in a manner similar to Systems L1-L6 in that there is heat transfer between the storage material (water) and refrigerant during charging for heating or cooling storage. The subsystem is then discharged by circulating the storage water through an indoor water-to-air heat exchanger. A single indoor heat exchanger that serves to provide for refrigerant-to-air, refrigerant-to-water, or water-to-air heat exchange is assumed to be available for this purpose. Finally, a storage domestic hot water system has also been included for evaluation.

Four baseline systems are also being considered for comparative purposes. System B1 is a conventional heat pump, B2 a fossil furnace combined with a vapor compression air conditioner, B3 an electric furnace coupled with an air conditioner and B4 which is a conventional domestic hot water system.

SYSTEM PERFORMANCE

Steady state performance characteristics, i.e. capacity and input power required to drive the system during each possible mode of operation, have been completed for each of the TES and baseline systems. Performance characteristics were obtained from actual empirical data supplied by the manufacturers or from available computer simulation models. Each TES system's performance was computed for storage capacities of 100, 200, 300, 400, and 500 KBtu and for those systems coupled with an air conditioner or heat pump for 3-, 4-, and 5-ton HVAC equipment (in the case of Systems L9 and L10 a 2-ton system was also simulated for load leveling considerations).

A computer simulation developed by RTI was used to compute performance characteristics of the baseline heat pump System B1 and the six latent heat TES/heat pump Systems L1 through L6. Charging and discharging performance characteristics of ice storage Systems L7 and L8 were computed using algorithms developed by Carrier Corporation to predict performance of heat pump and air conditioner coupled cool storage systems. Conventional performance characteristics of System L7 are those of the baseline System B2, a Carrier model 38RE air conditioner and a fossil furnace. Performance of System L8 during conventional operation is that of System B1.

A computer simulation developed at the University of Delaware Energy Institute was utilized to compute charging and discharging performance of the heat pump assisted Chub Systems L9, with storage for cooling applications, and L10, with storage heating.

Performance characteristics of the sensible heat system S1, a pressurized water system, was determined primarily from operational information for the 245 gallon Megatherm Residential Electric Thermal Storage System supplied by the Megatherm Company. Conventional performance of this system is that of System B3. Performance of the unpressurized hot water system S3 is identical to that of System S1. Performance for System S2 has been developed partially based upon the characteristics of a similar commercially available system. System S4 is similar to the Solaround™ heat pump system and will be characterized based on the performance of this commercially available system.

THERMAL LOAD CHARACTERIZATION

In order to properly evaluate the performance of each system, they must be required to satisfy realistic heating and cooling loads. These thermal loads have been computed using the TRNSYS computer simulation. The methodology used in this model follows ASHRAE recommended procedures which utilize transfer functions for calculating conduction heat gains and losses. These heat gains/losses are then combined with other specified or computed, sensible, and latent heat loads to determine the total hourly thermal load on the house. The assumption made in this analysis is that the heating/cooling system will exactly satisfy these load requirements. The computation of these thermal loads requires that hourly weather data be provided for the entire simulation period along with general building design and construction characteristics. SOLMET meteorological data was used as the needed climatic data while a "typical" house design and construction was defined for each of the climatic regions considered.

SYSTEM SIMULATION

A computer simulation has been developed that serves to simulate the operation of each system as it responds to the building thermal loads. This response is determined by a control algorithm which duplicates actual sytem operation under any imposed TOD rate structure. Both load shifting and load leveling control algorithms will be considered. System steady state performance, building thermal loads, meteorological data, and a description of the electric utility rate structure are required as inputs.

The simulation has been designed to allow modeling of several control strategies and special control blocks may easily be placed into the model for exact simulation of specific systems and control strategies. The hourly results provided by this program consist of peak electrical demand, state of storage charge, operative system modes, and electrical energy consumed.

SYSTEM ECONOMICS

The economic performance of each system will be based upon the energy costs associated with the operation of the system and a total annualized life cycle cost associated with the purchase and operation of the system. Each of these criteria is a significant function of the electric utility rate structure under which the system must operate. The demand, energy, and customer charge components each play an important part in the projected cost effectiveness of each system. Through this analysis, as in the development of energy use characteristics, the primary scope of activity will involve comparing between systems operating in the same climatic location. The approach to be utilized involves analyzing the technical and economic performance of each system from the point-of-view of the individual owner.

Conceptual cost estimates for the various thermal energy (TES) and baseline heating, ventilation, and air conditioning (HVAC) equipment have been generated to be used along with results of the system simulations of technical performance to identify cost-effective storage alternatives. An equipment list has been specified for each TES/HVAC system so that a total system cost can be estimated.

Sufficient cost detail has been obtained to enable estimates of conventional HVAC equipment costs to be generated as a function of size or capacity for major pieces of equipment. Hence, equipment cost estimates for heat pumps, air conditioners, and other HVAC equipment have been obtained as packaged units available on a contractor basis from retail distributors. The primary sources of this data were vendor quotes, previously published reports, or equipment cost surveys.

TES system cost data was determined when necessary at the component level of detail. Since some of the storage systems investigated were not commercially available, equipment costs were developed by obtaining estimates for components, and then factoring up an estimate for the overall piece of equipment based on design specifications.

Life cycle cost associated with the purchase and operation of the systems will be computed as an annualized stream of payments. The energy cost associated with the operation of each system will be computed based on the hourly energy use and demand computed with the system simulation along with the imposed values of the three components of the electric rates.

PROJECT STATUS

Hourly building thermal loads for each of the simulation sites have been computed and along with meteorological data has been processed for input to the hourly system simulation. Steady state performance has been established for each of the systems except System S4 which awaits information from the manufacturer of a similar system.

System capital costs have been established for each system. Capital costs for conceptual systems that are not commercially available are currently being modified to reflect those costs that would exist if the system was a mature, commercially available system. This will better establish a consistent set of capital costs between systems. The computer programs required to scale component costs to a total system capital cost and to compute annualized life cycle cost have each been coded and successfully tested.

The operational simulation has been coded and is presently undergoing an extensive testing procedure to verify the accuracy and proper operation of the program. This testing should be completed with 2-3 weeks at which time production runs can be initiated.

Activities to be completed in the immediate future include completing the definition of all steady state performance characteristics and further testing of the operational simulation. Specific cases to be simulated are also in the process of being defined. This will involve specification of those combinations of system, site, and rate structure to be considered in the final analysis.

ACKNOWLEDGEMENT

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ASSESSMENT OF COOL STORAGE TECHNOLOGIES

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ABSTRACT

As part of its storage assessment program, Argonne National Laboratory is evaluating cool storage technologies for electric load leveling in commercial building applications. Analysis of conventional chilled water and ice storage systems indicate that paybacks of less than four years are available under the partial storage mode of operation. Full storage systems entail larger initial capital outlays and longer paybacks under existing commercial-class electric rate schedules. Improved performance and lower costs could be achieved through R&D to improve the match between the storage and the chiller systems and through development of improved latent heat systems.

I. INTRODUCTION

As part of its storage assessment program, Argonne is evaluating cool storage technologies for electric load leveling in commercial building applications. The basic objectives of the study are to define the technical requirements of cost-effective storage devices and to establish R&D cost/performance goals.

Earlier work at Argonne has examined customer-owned storage in residential electric load leveling and solar heating applications.[1-6] In these studies, it was generally concluded that electric storage heating represented a cost-effective method of load management in service areas supplied by winter-peaking electric utilities, but that residential cool storage was only marginally cost-effective in service areas supplied by summer-peaking utilities. Analysis of storage in residential solar heating determined that storage was a necessary component of active solar systems if the systems were sized to meet a significant fraction of the daily heating load. However, on a total (utility plus customer) cost basis, the solar systems generally were not cost-competitive with load managed electric systems.

The extension of the assessment of cool storage to cover the commercial building sector was prompted by the following observations:

- cool storage exhibits significant returns to scale, that is, the unit cost of storage decreases as the size of the storage system increases;

- the daily cooling cycles of commercial buildings are often of relatively short duration because of the short building occupancy period, thereby enabling a given amount of storage capacity (kWHs) to displace a proportionately greater demand (kWs) from the peak to the off-peak period;

- electric demand charges (or other marginal-cost-based electric rates) are more prevalent in the commercial sector than in the residential sector;

- commercial building applications usually offer greater opportunity for control of the operation of the cool storage equipment.

The balance of this report summarizes technical progress on the assessment of cool storage in commercial buildings. Section II discusses the performance and cost of cool storage systems, defines alternative modes of operation of these systems, and describes the interface with conventional chiller systems. Section III describes the method used to estimate payback on investment in cool storage and, finally, Section IV makes several R&D recommendations to improve the performance and economics of cool storage in commercial building applications.

II. COOL STORAGE TECHNOLOGY AND COSTS

Conventional cool storage systems are based on either ice-making (latent heat) or chilled water (sensible heat) storage. The basic principle of operation is to shift a substantial part of the electrical requirement for building space cooling from the utility's peak to its off-peak period. Depending upon changes in the temperature regimes faced by the evaporator and condenser coils of the chiller, this shifting of the electrical load will affect the number of kilowatt-hours consumed by the customer; it may, in fact, lead to increased consumption. The load shifting, however, will reduce the demand, or capacity, component of cost and will enable the utility to supply more of the customer's electrical requirement with lower-cost off-peak fuel. An added conservation benefit accrues because the off-peak utility generating plant is generally more energy-efficient than the plant used to supply on-peak electricity.

Whether ice or chilled water storage is used, a key consideration, affecting the sizing and operation of the storage and chiller components, is the mode of operation selected.

Full vs. Partial Storage

Under the full storage mode of operation, the compressor and storage capacities are selected to enable the system to supply most of the building cooling needs during the peak period from storage. In this mode of operation, the chiller is switched off during the peak period so that the only cooling-associated loads during the peak period are those due to the operation of water circulation pumps and blowers in the building water distribution and air handler systems. Storage capacity must be adequate to meet the time-integrated building load during the peak period plus the thermal losses from storage on the design day. The full-storage concept minimizes the contribution of the building cooling load to the utility's coincident peak load.

Under the partial storage concept, the storage and chiller capacities are set by the criterion that the design day load be met by continuous operation of the chiller at rated output. This mode of operation minimizes the chiller capacity requirement. The load profile and the capacity trade-offs for conventional, full-storage, and partial-storage HVAC systems are illustrated in a simple way in Figure 1.

Latent vs. Sensible Heat Storage

Water-based cool storage systems make use of either the sensible heat content (1 Btu/°F/lb) or the latent heat of fusion (144 Btu/°F/lb) of water.

An important consideration in the design of sensible storage is the inlet temperature requirement of the water distribution system. For reasons of humidity control and adequate heat exchange at the air handler, the water temperature at the inlet to the distribution system is generally held to 48°F or less, corresponding to a return temperature on the design day in the range 55-59°F. Thus, because the temperature swing available for sensible heat storage is constrained to lie between the freezing point of water and 48°F, the maximum ΔT for design purposes is approximately 15°F.

If the sensible heat storage system incorporates a

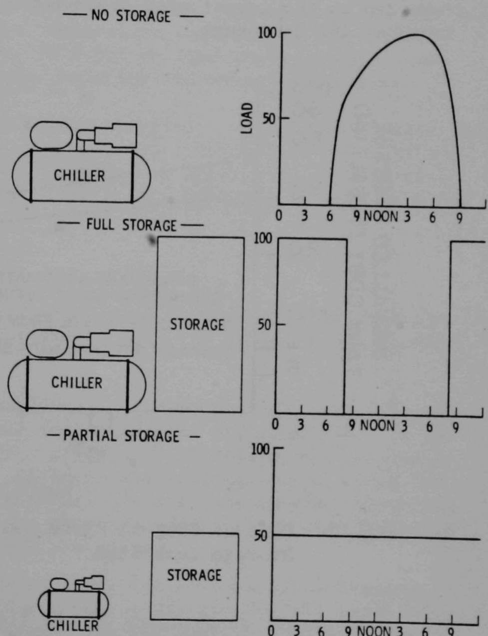

Fig. 1. Operating Modes for Cool Storage Systems

stratified chilled water storage tank, the water supplied to the distribution system from the bottom of the storage tank can be held to 40°F, the temperature at which the specific gravity of water is greatest. In principle, under conditions of perfect stratification, this temperature can be maintained over the entire diurnal cycle. If the return temperature from the air handler systems rises to 58°F on the design day, the ΔT available for storage is 18°F. In practice, the finite thickness of the stratification layer in the storage tank will cause the temperature at the inlet to the distribution system to rise above 40°F on the design day if the storage tank is sized under the assumption of perfect stratification. Experience with the operation of stratified cool storage tanks indicates that the degradation caused by such effects is about 20% of original design capacity. Thus, for design purposes, a ΔT equal to 15°F again can be assumed.

The unit cost of chilled water storage varies widely, depending on such factors as storage tank material, storage size and location, and whether the storage is for old or new construction. Figure 2 presents cool storage costs as a function of storage size as determined by recent engineering design studies and actual experience in constructing storage tanks.[7] The storage costs shown in the figure refer to bare tank costs, in this case the cost of cast-in-place concrete tanks. Such tanks are generally regarded as the lowest cost storage for capacities in excess of 40,000 gallons, or 400 ton-hours.

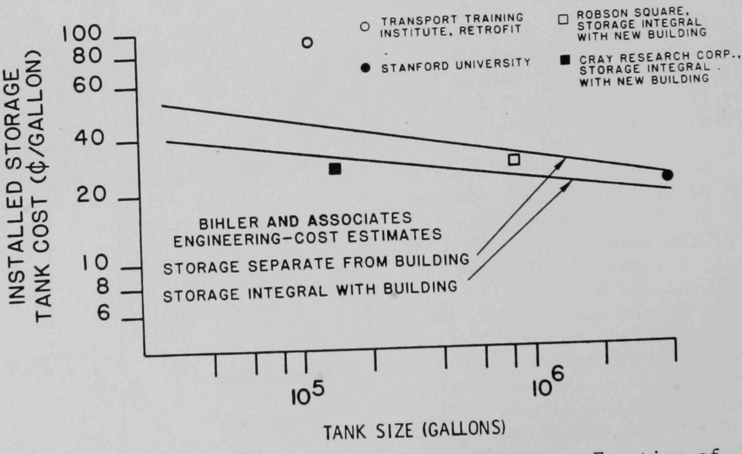

Fig. 2. Cost of Cast-in-Place Concrete Tanks as a Function of Storage Tank Size

To obtain an estimate of the total cost of chilled water storage systems, the cost of piping, controls, and instrumentation must be added to the tank costs. Two recent cost studies, one based on an engineering cost analysis,[8] the other on actual experience at Robson Square,[9] indicate that the cost of the basic storage tank should be increased by approximately 50% to account for balance-of-system costs.

The chief advantage of ice over chilled water storage is the smaller storage volume required. Were it possible to cycle the entire storage volume between solid and liquid phases, an ice storage system would offer an order-of-magnitude volume reduction relative to a chilled water system with $\Delta T = 15°F$. In practice, because of the need to maintain part of the storage medium in the liquid phase (for circulation and heat transfer) and because of the presence of evaporator coils in the ice-building systems, the volume savings are limited to about a factor of six.

Ice systems fall into two general categories: static (ice-building) systems and dynamic (ice shucking or slurry) systems. In the static systems, ice is formed on evaporator coils incorporated into the storage tank itself. The static systems include ice-thickness control and either internal baffling or water agitation for efficient heat transfer from ice surfaces during the melting cycle.

Dynamic ice storage systems manufacture ice in crushed or chunk form and deliver it for storage in large bins. The storage tanks for dynamic systems are similar in design and operation to those used in the chilled water systems.

An inherent disadvantage of the ice systems, relative to the chilled water systems, is the lower suction temperature required of the chiller, typically 10°F for ice building vs. 30°F for chilled water systems, causing significant reductions in chiller capacity and energy efficiency.

The cost of ice storage, including shipping costs and contractor installation, overhead, and profit, is approximately $0.60 per pound of ice capacity for packaged systems of 45,000 pound capacity. Unit costs rise with smaller size, to approximately $1.65/lb for packaged systems of 4,000 lb capacity.

Chiller Systems

The storage systems described above must be matched with an appropriate chiller system and integrated into a complete building air conditioning system.

Three types of compressive chillers -- reciprocating, centrifugal, and screw -- are currently available for commercial building use. In recent years the range of applicability of screw compressors has been extended to approximately 800 tons. Although the application of screw compressors to space conditioning is a relatively new development, occurring within the last seven or eight years, screw compressors have been used in the refrigeration field for about fifteen years.

Figure 3 shows installed system costs for systems incorporating packaged compressive chillers.[10] The system costs include the costs of the packaged chiller, the cooling tower, and the condenser water pumps, plus installation costs, including contractor overhead and profit. As indicated in the figure, reciprocating systems represent the lower cost alternative below 120 tons capacity, while screw-type compressors are less expensive above 120 tons.

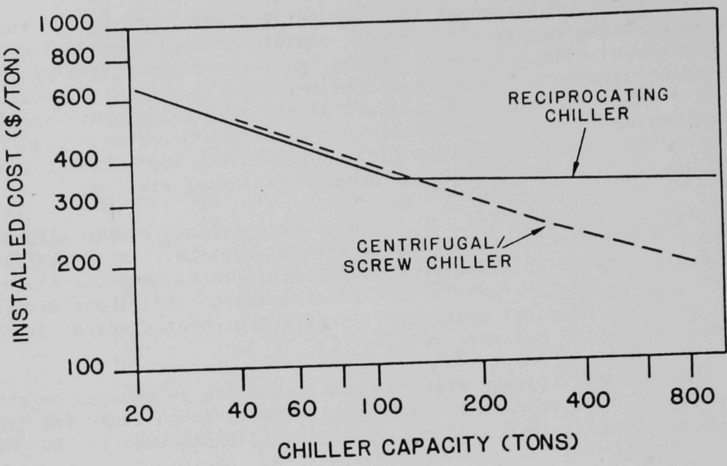

Fig. 3. Costs of Installed Chiller Systems

Compressor performance depends on the saturated suction temperature (SST) and saturated discharge temperature (SDT). For a constant SDT, compressor capacity and coefficient of performance (COP) decline with decreasing SST. On the other hand, for constant SST, both capacity and COP increase with decreasing SDT.

Because the operation of a storage system involves a lower SST than does the operation of a conventional cooling system (SST equals 30°F for chilled water and 10°F for ice storage vs. 34°F for a conventional system), chiller performance is correspondingly diminished. This loss in performance may be partly or completely made up, however, by the lower SDT available to cool storage systems. The lower SDT occurs because of proportionately longer operation of cool storage systems during the nighttime hours when outdoor temperatures are lower.

III. EXAMPLE APPLICATIONS

The overall costs of installing and operating cool storage systems were compared with the costs of conventional systems in representative commercial buildings in two service areas. One service area is located in the Mid-Atlantic region, the other in the Midwest. Both are supplied by summer-peaking utilities that have adopted peak load rates for large commercial-class customers. Eight buildings (four in each service area) were analyzed; results for one of the buildings in the Mid-Atlantic service area are presented here.

Load Analysis

Actual building electric loads, measured on a 15-minute interval basis by the local utility, were used to characterize the building cooling loads. To size both the conventional and the cool storage HVAC systems, it was necessary to estimate thermal cooling loads under design-day conditions. A two-step procedure was used to separate the measured building electrical loads into weather-sensitive (thermal) and weather-neutral (non-thermal) components. First, a weather-neutral load profile was estimated for each weekday by identifying that Spring day with minimum integrated building load (holidays excluded). Next, the Summer day with maximum demand was identified. The design-day hourly cooling load was then estimated as the difference between the profiles on the peak and weather-neutral days.

Engineering Design

The cooling system was assumed to consist of a central-electric chiller, cooling tower, auxiliaries, and a water distribution system having an inlet water temperature of 44°F. The electric chiller, a screw compressor, was assumed to have a COP of 3.5. Under these assumptions, one ton-hour of building thermal load corresponded to an electrical requirement of one kilowatt-hour.

The following sizing criteria were used:

Conventional System: The conventional systems were sized to meet the annual peak hourly thermal load.

Partial Storage System: The partial storage systems were sized to meet the time-integrated thermal load on the design day under continuous operation of the compressor. Although the compressor operates continuously at full capacity on the design-day, changes in compressor performance with day-night variations in suction temperature have the effect of reducing the nighttime electrical load relative to the daytime load.

Full Storage System: The full-storage systems were sized to minimize building peak electrical load during the peak demand period by shifting the cooling load into the off-peak, nighttime period.

The sizing of the ice systems included an adjustment to account for the non-linear buildup of ice on the evaporator coils over time. A set of relationships developed by Caloskills was used for this purpose.[11]

System Costs

Component sizes and costs for the different cooling system alternatives under the partial and full storage modes of operation are shown in Table 1. The capital costs of the cooling system incorporating partial storage are about 70% higher than for the conventional cooling system, the added costs of storage being partly offset by the chiller capacity savings.

Table 1. System Sizes and Costs

Equipment Description	Conventional	Partial Storage: Ice-Building	Partial Storage: Chilled Water	Full Storage: Ice-Building	Full Storage: Chilled Water
<u>Component Sizes</u>					
Compressor (Tons)	2-805	2-395	2-330	2-810	2-535
Storage Tank	--	5,600 ton-hr	792,000 gal	12,760 ton-hr	1,304,000 gal
Storage Volume	--	20'x25'x25'	20'x70'x75'	20'x35'x40'	20'x90'x95'
<u>Compressor Demand (kW)*</u>					
Daytime	1605	790	655	0	0
Nighttime	--	695	560	1430	905
<u>Component Costs (1980 $\$10^3$)</u>					
Chiller System					
Chiller	211.9	143.7	129.6	213.2	171.4
Cooling Tower	55.2	28.7	23.7	55.7	36.6
Condenser Pump	8.3	4.3	3.8	7.4	5.5
Installation	26.6	12.9	11.4	26.9	17.7
Storage System	--	320.9	309.5	556.1	467.4
Total	302.0	510.5	478.0	859.3	698.6

*Represents electrical load under design-day operating conditions.

Both the ice-building and the retrofit chilled water systems cost substantially more than the conventional system.

As indicated in the table, the capital costs of full storage systems are substantially greater than the capital cost of the partial storage system.

Customer Payback Analysis

Because the storage systems entail a higher initial cost than the conventional cooling system, the cost-effectiveness of storage depends upon savings available under the applicable electric utility rate schedule. Customer bill savings were computed under the rate schedule currently in force in the Mid-Atlantic service area. The rate schedule is a time-of-use schedule incorporating energy and demand changes and three daily and two seasonal demand periods.

Monthly energy and demand changes were computed and summed over an annual cycle to determine annual bills for the different systems. Table 2 presents annual energy consumption and peak demands and the associated bill values for each of the cooling systems.

Simple paybacks on investment in the alternative storage system were calculated based on the system bill savings in Table 2 and the system costs given in Table 1. The results are presented in Table 3. These results for this example application, combined with results for the other seven buildings, led to the following conclusions:

- Partial storage systems, because of their smaller compressor capacity requirements, involve substantially lower capital outlays by building owners than do full storage systems; partial storage also offers faster payback than full storage.

- For the storage cost values used in this analysis, chilled water storage offers a faster payback than ice systems in new applications. Ice systems may have the advantage in retrofit applications.[12]

- Storage is more economical in buildings with short daily occupancy periods and narrow cooling loads than in buildings with longer occupancy periods.[12]

IV. RESEARCH AND DEVELOPMENT NEEDS

The analysis of cool storage described above is based on adoption of commercially available hardware components. Refinement of these devices for optimal application in storage systems will improve their performance and reduce costs. Manufacturers of tanks, ice builders, and similar devices have begun to address improvements to their products and marketing approaches. Further technology development requires public-sector partici-

Table 2. Annual Cooling Loads and Bill Values

System	Cooling Load		Annual Bill		
	Peak* (kW)	Energy (MWh)	Demand (10^3\$)	Energy (10^3\$)	Total (10^3\$)
Conventional	1605	1859	116.2	54.8	171.0
Chilled Water					
Partial Storage	655	1715	47.7	49.2	96.9
Full Storage	0	1584	0	43.6	43.6
Ice-Building					
Partial Storage	790	2095	57.5	60.1	117.6
Full Storage	0	2448	0	67.5	67.5

*Refers to contribution of cooling load to building peak demand during peak demand period.

Table 3. Payback on Investment in Cool Storage

System	Bill Savings (10^3\$)	Incremental Investment (10^3\$)		Payback (Years)	
		New	Retrofit	New	Retrofit
Chilled Water					
Partial Storage	74.1	176.0	330.7*	2.4	4.5
Full Storage	127.4	396.6	630.3*	3.1	4.9
Ice-Building					
Partial Storage	53.4	208.5	208.5	3.9	3.9
Full Storage	103.5	557.3	557.3	5.4	5.4

*Based on a retrofit cost for the storage component of a chilled water system equal to 1.5 times the cost for a new system.

pation due to the inherent levels of risk and delays in return on RD&D efforts. Several R&D needs have been identified for DOE consideration, and their requirements and potential benefits are being addressed. These include:

- Development of chillers and heat pumps to improve performance in the temperature regimes presented by cool storage systems;

- Identification of media and devices for cool storage at common utilization temperatures (38-44°F, 3-7°C) including consideration of sensible, latent, and reaction heat storage approaches;

- Evaluation of heat recovery potential in cool storage charging;

- Examination of economies of scale in even larger applications, for example, in central and district heating and cooling systems; and

- Development of techniques for reduction of storage losses due both to mixing and to parasitic burdens.

A fuller discussion of these issues will be provided in a forthcoming report.[12]

REFERENCES

1. *Electric Storage Heating: The Experience in England and Wales and in the Federal Republic of Germany*, J.G. Asbury and A. Kouvalis, ANL/ES-50, April 1976.

2. *Assessment of Energy Storage Technologies and Systems, Phase I: Electric Storage Heating, Storage Air Conditioning, and Storage Hot Water Heating*, J. Asbury, R. Giese, S. Nelson, L. Akridge, P. Graf, and K. Heitner, ANL/ES-54, Oct. 1976.

3. *Solar Energy and Electric Utilities: Should They Be Interfaced?*, J.G. Asbury and R.O. Mueller, article in Science, Feb. 4, 1977.

4. *Assessment of Energy Storage Technologies and Systems, Phase II: Heat Pump and Solar Energy Applications*, J. Asbury, J. Caruso, R. Giese, R. Mueller, L. Akridge, K. Heitner, A. Molander, P. Moritz, ANL/SPG-3, March 1978.

5. *Electric Storage Heating in New England: Field Test and Assessment*, H. Hersh, S. Nelson, J. Asbury, Proc. of the American Power Conference, April 1980.

6. *Heating with Electricity: The Right Price at the Right Time*, J.G. Asbury, R.F. Giese, and R.O. Mueller, article in Technology Review, Dec/Jan. 1980.

7. B+A Engineers, Ltd., Chicago, unpublished information, July 1980.

8. *Thermal Storage: Resisting Temperature Blending*, R.T. Tamblyn, ASHRAE Journal, Jan. 1980.

9. *Thermal Storage in Robson Square, Vancouver, British Columbia*, E.I. Mackie, ASHRAE Transactions 1980, DV-80-8, No. 1, 1980; also private communication with E.I. Mackie, Jan. 1981.

10. *Concurrent Construction Costs 1980*, 17th Annual Edition, Lee Saylor, Inc., Walnut Creek, California, 1980.

11. *Thermal Energy Storage Systems*, Caloskills, a Division of Girton Manufacturing Co.

12. J. Asbury, J. Calm, and R. Giese, Argonne National Laboratory, unpublished information.

IMPACT OF CUSTOMER SIDE THERMAL ENERGY STORAGE ON ELECTRIC UTILITY LOAD MANAGEMENT†

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ABSTRACT

The issues of using distributed thermal energy storage by electric utility customers is discussed. Public acceptance on the part of actual users and institutional/legal barriers are reviewed. An economic benefit/cost model is presented. Empirical results based on data provided by six electric utilities are presented. It is shown that time-of-day rates would be desirable for the more widespread use of decentralized thermal energy storage systems.

INTRODUCTION

Traditionally, electric utilities have ameliorated peak-load costs by developing central storage, such as hydro on the utility side of the meter. Although this is a fine solution, it is not as attractive as it once was. First, in many instances hydro-storage sites are becoming more difficult to locate; second, extremist environmentalists are delaying their exploitation; third, construction costs are high and financing is costly. There are, then, two alternatives open to the utilities. First, to exploit alternative energy such as wind energy conversion, etc.; second, to promote energy storage on the customer side of the meter. The first, although technologically promising, involves some risk and institutional uncertainty. A more immediate solution to minimizing the cost of providing for peak-load demand is to consider energy storage at the customer side of the meter. This may be done in a number of ways. In this paper we will address ourselves to thermal (TES). Although the benefits of TES cannot be denied, it is not used widely. We believe that this is due to the fact that the overall evaluation is extremely complex and involves TES technology, the economics of installing TES, utility generating capacity, financing utility construction, regulatory practices, living styles and alternate rate structures. Accordingly, the Advanced Conservation Technologies Division of the Department of Energy awarded a contract to the Office of Energy Programs of The George Washington University to look at the problem in

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† Conducted under contract #DEAC 0178 ET 26963.

a comprehensive manner. To be responsive to our assignment, we assembled an interdisciplinary team of engineers, economists, sociologists and psychologists. We are gratified by the positive help that investor-owned electric utilities, individual consumers, financiers, developers, and local governments gave us freely to make our results more realistic.

Although our ongoing study does involve numerous disciplines, it may be divided into two basic fundamental areas: (a) sociological/behavioral factors including institutional/legal constraints; and (b) techno-economic requirements. Each of these has its subsets. In the present paper we will, as requested by the Argonne National Laboratory, our host of this meeting, emphasize the latter.

FINDINGS

1. Psychometric Studies. After preliminary analysis on the campus, the bulk of this study was performed in the field, particularly in Vermont where there are TES units. These are imported from the German manufacturers. In studying the problem, the Decision Analysis Panel approach developed by J.B. Margolin[1] was used. Individual consumers and two utilities, i.e. Central Vermont Power Company and Green Mountain Power Company, participated. Both the utilities and the individual consumers were favorably inclined to TES. However, the following were felt to be desirable: (a) Technical Modifications: (a.1) for central home systems; (a.2) thermostat for lower settings; (a.3) indicator lights; (a.4) redesign to remove decorating obstacles and safety hazards; (a.5) improved sensor systems to achieve better anticipation of weather changes. (b) Government Assistance: (b.1) direct or indirect subsidies to overcome front-end cost of TES; (b.2) information services; (b.3) participation in the decision making process. (c) Institutional: (c.1) greater acceptance by builders and developers; (c.2) reduction in front-end costs; (c.3) improved servicing.

2. Institutional/Legal Considerations. The implementation of TES requires institutions (i.e. lending institutions and insurance companies) and legal jurisdictions (i.e. permits, licenses, codes) to be encouraging. Our study[2] indicates that there are no prohibitions but that, indeed, there are no encouragements. In this part of our study we contacted representatives of the principal sectors influencing the barriers and incentives to non-solar, thermal energy storage. In very brief terms our findings are: (a) there is a distinct information gap about the advantages of thermal energy storage; (b) there is a lack of infrastructure to properly install and maintain TES; (c) there is lender reluctance caused by lack of knowledge and the fear of risk; and (d) there are inadequate Federal incentives -- direct and indirect.

3. Econometric Cost-Benefit Analysis. In this phase of our study, we attempted to answer two related questions: (a) when does it make sense to the consumer to install his/her thermal energy storage system? (b) what would be the impact on the supplying electric utility when its customers install TES? Because the desirability of TES depends on the rate structure, we considered three different scenarios: (a) time-of-day (TOD) rates; (b) time-invariant rates with subsidy; and (c) time-invariant rates without subsidy but with load control devices.

Possibly the most extensively analyzed method of dealing with the peak-load problem is the introduction of time-of-day (TOD) pricing. Under TOD pricing the cost of electricity to consumers at each instant is set equal to the marginal cost of supplying that electricity at that instant. Consequently, electricity would be more expensive at times when demand was high than at times when demand was low. Neglecting implementation costs, such a pricing system can be shown to be economically efficient.[3,4,5]

Direct load controls are one alternative to TOD time-specific pricing. Under a system of direct load controls, the price of electricity would be time invariant, and the utility would be able to shut off or limit each customer's purchases of electricity during peak hours. Storage allows customers to relax the link which exists between purchases of electricity and consumption of energy.

A second alternative to TOD pricing is subsidization of storage. If customers with TES in their homes were granted rebates on their monthly electricity bills, investment in these devices would clearly be encouraged.

The tool that economists use when studying questions of this sort is cost-benefit (C/B) analysis. The notion underlying C/B analysis is that a project yields net benefits to society if those who would gain from its implementation could compensate those who would lose and still feel better off (Pareto economics).[6] In general, the desirability of any load management technique will depend not simply upon its effect upon the load factor of a utility company, nor only upon the savings in production costs which result from its implementation, but also upon its effects on consumers. This paper attempts to consider these effects explicitly.[7]

<u>3.1 The Actors</u>. There are three sets of actors which enter into the analysis. First, there is a set of customers. Each customer must first decide how much storage capacity he/she will invest in. This decision will depend, among others, upon the personal preferences of the consumer, the cost of storage equipment net of any subsidies which might be offered, the efficiency of available equipment, and the prices of peak and off-peak electricity. In the analysis which follows, it will be assumed that a particular subset of each individual's energy needs will be met out of storage during peak periods and only out of storage. Under certain further assumptions about the structure of the load management techniques employed and the parameters of the customers' decision problems, each individual will always fully charge his/her storage system during off-peak hours. The quantity of electricity consumed by an individual in the off-peak period will depend only upon his/her personal preferences and the price of electricity at that time. Energy derived from TES will be determined completely by the investment.

The second actor in the analysis is the electric utility company. The utility is unable to influence the timing or quantity of electricity purchases under the peak-load pricing system. Under the one-price system there will, of course, be time switches installed in people's homes. But the rules governing the operation of these switches will here be assumed to be an integral part of system structure, fixed by the public utility commission.

The final actor in the analysis is the public utility commission (PUC). It is the PUC which determines the price to be charged for electricity, and the subsidy, if any. These decisions, like the utility company's concerning base-load capacity and the customers' concerning investment in storage equipment are taken to be revised only infrequently in response to sustained shifts in conditions. Just as the utility company must take into account the behavior of consumers when deciding upon the size of its generating plant, so must the PUC take into account the response of both the utility company and its customers.

3.2 The Model. A model offers the advantage of comparing different outcomes without the policymaker having to make decisions that may be economically costly and socially disturbing if implemented. Another advantage of a model is that it can handle far more many variables than the human mind can cope with. In our model there are involved fifty complicated, functional relationships. The scope of this paper does not allow us to present them or their derivations.[8] The assumptions made in developing the model were: (a) implementation costs associated with alternative load management strategies were not included; (b) the demand for peak and off-peak electricity and energy from storage are independent of each other and are solely a function of the respective price of electricity during the peak and off-peak periods and the price of energy from storage; (c) in the short-run, each customer's storage capacity is fixed; (d) the study relates to the residential class of customers only; and (e) the cycle is a 24-hour daily cycle with a single peak and off-peak period.

Qualitative conclusions that may be derived from the model are: (a) Ignoring differences in the relative cost of implementing the various strategies, time-invariant rates with subsidized storage were found to be inferior to peak-load pricing but superior to direct load controls. (b) Under peak-load pricing the incentive to invest in TES is present in just the proper degree. Even with time-invariant rates, a schedule of subsidies can be established which will result in an efficient distribution of storage equipment. (c) All these results could have been obtained in a framework much more general than that employed in the current paper. Our additional assumptions enables us to derive explicit formulas for differences in the net social benefits derived from each load management system, for the prices and/or subsidies needed to implement them, and for the generating and storage capacities. By substituting estimates of the relevant parameters into these formulas, utility companies and PUCs should be able to obtain useful information on the long-run benefits, costs, and consequences of alternative load management strategies. (d) The biggest weakness in the current paper is probably the assumptions relating to the independence of the demand for peak and off-peak electricity, and those related to the extent to which storage capacity will be utilized. Simply dividing time into peak and off-peak periods and introducing peak-load pricing may result in the formation of a demand spike in the hours just prior or just subsequent to the peak period. (e) More difficult to eliminate are the assumptions that under peak-load pricing TES will always be fully utilized and never supplemented with peak electricity. This suggests that the formulas derived in the current paper, if anything, understate the desirability of peak-load pricing relative to other load management techniques. It may be possible to generalize the analysis somewhat, allowing more accurate calculations, by distinguishing between storage for different purposes.

3.3 Empirical Evaluation. While the model does provide insights, it does not consider to what degree different electric utilities are likely to be affected. To do so, one requires actual data applicable to individual utilities. Of the utilities that we contacted, six generously provided data. These are: Baltimore Gas and Electric Company, Green Mountain Power Company, Gulf Power Company, Pennsylvania Electric Power Company, Potomac Electric Power Company, and Virginia Electric Power Company. To conduct the numerical analysis we developed a computer program representing our model. The inputs (independent variables) were: 1) number of customers; 2) average production cost of off-peak electricity ($/kWh); 3) rate of increase of production costs of output excess of base-load capacity ($/kW/kWh); 4) cost per unit of time of base-load generating capacity ($/kWh); 5) rate of decline of marginal valuation of off-peak consumption ($/kW/kWh); 6) rate of decline of marginal valuation of on-peak consumption ($/kW/kWh); 7) rate of decline of marginal value of consumption of energy from TES ($/kWh); 8) cost of storage equipment ($/kWh); 9) length of off-peak period (hrs); 10) length of on-peak period (hrs); 11) efficiency of storage equipment; 12) intercept of typical demand curve for off-peak electricity ($/kWh); 13) intercept of typical demand curve for on-peak electricity ($/kWh); and 14) intercept of typical demand curve for energy from TES ($/kWh). There were twenty outputs: 1) advantage of peak-load pricing over one-price with subsidy, net social benefits/customer ($); 2) advantage of one-price without subsidy over one-price with controls but without subsidy, per customer ($); [for the peak load case] 3) price of off-peak electricity ($/kWh); 4) price of on-peak electricity ($/kWh); 5) total storage (kW); 6) expected total demand for off-peak electricity (kW); 7) expected total demand for on-peak electricity (kW); 8) expected base-load generating capacity (kW); [for the single price with subsidy to storage] 9) price of electricity ($/kWh); 10) subsidy of storage equipment ($/kWh); 11) total storage (kW); 12) total subsidies for storage ($); 13) expected total demand for off-peak electricity (kW); 14) expected total demand for on-peak electricity (kW); 15) expected base-load generating capacity (kW); [for the single price with no subsidy to storage but with direct load controls] 16) price of electricity ($/kWh); 17) total storage (kW); 18) expected total demand for off-peak electricity (kW); 19) expected total demand for on-peak electricity (kW); and 20) expected base-load generating capacity (kW). Our program allowed us to vary ranges within any four variables at one time. Our numerical calculations confirmed our qualitative conclusions, albeit in varying degrees, for the six utilities which provided data.

CONCLUSIONS

Our findings are as follows: (a) Ignoring differences in the relative cost of implementing the alternative strategies, time-invariant rates with subsidized storage were found to be inferior to TOD rates, but superior to time-invariant rates with direct load controls and subsidies to storage. (b) Having ranked our load management strategies in terms of net social benefits, we are naturally interested in the optimal prices and subsidies needed to implement these strategies. Under the TOD pricing system we have an optimal off-peak price which is equivalent to the expected marginal cost of electricity in the off-peak period and an optimal peak price which is equivalent to the expected marginal cost of electricity in peak periods. The optimal peak price in all cases is greater than the optimal off-peak prices. No subsidies to storage are offered under this system since market forces are sufficient to generate the optimal amount of investment in storage systems. (c) Under the single-price system with subsidy we have an optimal single price for electricity, which is a weighted average of the expected off-peak and expected peak marginal cost of electricity. (d) In comparing the alternative strategies we see that the optimal prices under the one-price system lie between the optimal peak and off-peak prices of the TOD pricing system. This is because with direct load controls and the absence of a subsidy to storage, changes in price affect the size of the investment customers are willing to make in storage equipment. (e) Investment in storage under the one-price system with direct load controls but no subsidies to storage falls short of the investment in storage, resulting from the implementation of peak-load pricing and the one-price system with subsidies to storage. In general terms, as the life-span of storage equipment increases, the level of investment in storage increases. (f) In terms of peak-load generating capacity, the utility company will wish to choose the load management strategy which will minimize its expected peak-load generating capacity. Since the utility company is assumed to be able to meet customer demand as it arises, and since the demand for electricity is a function of its price, it follows that the expected peak-load generating capacity is greatest under the single-price system with direct load controls and no subsidies to storage, followed by the single-price system with subsidies to storage, and least under TOD pricing. (g) The electric utility definition of "base-load capacity" is generally considered as that base-load plant which is operated 24 hours a day. Therefore, the conclusion is drawn that base-load capacity should be equal to that necessary to meet off-peak demand. Consequently, base-load capacity would be greatest under TOD pricing, followed by time-invariant pricing without subsidies to storage but with direct load controls and least under time-invariant pricing with subsidies to storage. (h) The above analysis, although appearing to be sound given the definition of base-load generating capacity employed by the utility industry, is structurally defective from an economic perspective. The rational aim of any utility should be to choose the long-run cost-minimizing base-load plant size and not simply one that is on-line 24 hours a day. In this respect, the decision on the optimum size base-load plant should be made on the basis of comparing the marginal savings resulting from the reduction of the expected costs of meeting peak demand due to each incremental increase in base-load capacity versus the cost of one additional increment of base-load capacity. Since the marginal cost of base-load capacity is assumed to be constant and since the demand for electricity on-peak is greatest under the one-price system without subsidies to TES and lowest under peak-load pricing, it follows that the cost-minimizing marginal cost base-load capacity is greatest under the one-price system without subsidies to storage, and least under TOD pricing. (i) We have seen that the alternative load management strategies imply different levels of investment in storage and varying levels of peak-load and base-load generating capacity. In an attempt to determine the relative impact of storage for the individual utilities we calculated investment in storage, as a percentage of peak-load generating capacity, for each of our pricing strategies. To the extent that storage capacity is a substitute for generating capacity, these figures give us an estimate of the possible gain due to a reduced need for generating capacity because of the existence of storage capacity.

RESEARCH IN PROGRESS AND PLANNED

Our analyses conducted so far and our discussions with practitioners in the field lead us to believe that our model is an innovative step in the right direction as far as laying the groundwork is concerned. However, because some of our assumptions are severe, we are in the process of making our work more useful.

The price elasticities of demand used thus far in our analysis are those based on the survey of the literature in the Fall 1979. The result of that survey led us to adopt a range of -.5 to -.625 for peak price elasticity of demand and a range of -1.0 to -1.25 for off-peak price elasticity of demand. Recently we launched an extensive investigation into the general area of price elasticities and attempted to differentiate price elasticities not only by TOD pricing, but also by season, by end use (cooling/heating), and by length of time. It appears that our original coefficients might be slightly on the high side. Complicating this problem is a study[9] which has just come to our attention based on a DOE Rate Demonstration Project for Arizona where price elasticities of demand with reverse rankings to those discussed above were found.

In our model the demand for peak and off-peak electricity and energy from storage are treated independent of each other and are solely a function of the respective price of electricity. Our psychometric studies made us suspicious of this assumption. In the framework of utility theory, our present rationalization implies that (a) there exists a utility function, and (b) since it exists, the only way to explain the willingness to pay function is to consider it as a transformation of the utility function, so that there occurs a maximization of utility subject to a fully spent income constraint problem. But the explicit way of doing it is to maximize a consumer surplus function. A consumer who maximizes his/her surplus with respect to choosing an optimal quantity is doing the same as one who maximizes utility. Some of our parameters are a compact way of symbolizing a more complex relationship between exogenous variables. It is not a good idea to conceal this relationship, particularly when the model is used empirically. We are in the process of determining the extent of any such bias and are refining our model by disaggregating our parameters.

In our model the implementation costs associated with the alternative load management strategies were not considered. This artifact simplifies the analysis but is not a comprehensive manner of ranking net social benefits. Accordingly, we are obtaining prices of the various off-the-shelf items (i.e. TES units, timers, switches, etc.) from manufacturers. These costs will then be factored into our analysis. When all of the above are completed, we plan to prepare a program that any electric utility or PUC can use readily to determine the best route to follow in its particular case.

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REFERENCES

1. Margolin, J.B.; "Socio-Economic Aspects of Thermal Energy Storage"; Behavioral Studies Group and Office of Energy Programs, The George Washington University; October 1979.

2. Kahan, C.V.; "An Analysis of the Institutional Barriers to the Widespread Use of Thermal Energy Storage Systems in Residential Construction"; Office of Energy Programs, The George Washington University; May 1979.

3. Asbury, J.G. and R.O. Mueller; "The Peak Load Problem with Storage Technology"; Energy and Environmental Systems Division, Argonne National Laboratory; August 1978.

4. Nelson, S.H.; "Strategies for Commercializing Customer Thermal Energy Storage"; Energy and Environmental Systems Division, Argonne National Laboratory; December 1976.

5. Steiner, P.O.; "Peak Loads and Efficient Pricing"; Quarterly Journal of Economics, Vol. 71; November 1957.

6. Harberger, A.; "Three Basic Postulates for Applied Welfare Economics"; Journal of Economic Literature; September 1971.

7. Electric Utility Rate Design Study; Rate Design and Load Control: Issues and Directions; National Association of Regulatory Utility Commissioners; November 1977.

8. Koenig, E.F.; "Electric Utility Rate Structures and Distributed Thermal Energy Storage: A Cost-Benefit Analysis"; Energy: The International Journal, Vol. 5; June 1980.

9. Atkinson, S.E.; "Responsiveness to Time-of-Day Electric Pricing: First Empirical Results"; Federal Energy Administration; May 1977.

ENERGY STORAGE FOR U.S. AIR FORCE GROUND POWER SITES

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ABSTRACT

This project will assess both the potential of adding energy storage systems to Air Force terrestrial applications as well as the utilization of advanced energy storage technologies to these applications. The effort will provide a characterization of USAF ground power applications with an emphasis on remote, mobile, and special applications. USAF applications will be identified in which energy storage can decrease a power generation system's life cycle cost and fuel consumption in addition to increasing the application's operational readiness and capabilities. An estimate of the values of adding energy storage systems to USAF ground power systems will be calculated. The project will identify the energy storage research and development needs for USAF terrestrial applications.

HISTORY

The "Terrestrial Energy Technology Program Office" was established in January of 1979. The office is located in the Energy Conversion Branch, Aerospace Power Division, Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB. The Aerospace Power Division is the center for energy research and development for USAF aerospace requirements. The office was established to adapt Department of Energy technologies to USAF ground power requirements while utilizing USAF technological experience and expertise in the energy arena. The program office was established with a charter to provide the research and development necessary to support mobile power systems, remote site power systems, and special purpose applications such as weapons systems support power, emergency power systems, and peaking power systems. The objectives of the terrestrial energy program include increasing force readiness, minimizing the impasse of rising energy costs, and reducing the vulnerability to energy supply disruption. Our efforts during the first year concentrated on fuel cells, Stirling engines, solar energy, technology assessments, and general requirements assessments.

While analyzing the requirements, it was determined that the potential existed for major improvements in USAF ground power generation systems with the addition of energy storage systems. This led to discussions with DOE at the "DOD-DOE Workshop on Joint Energy Activities" in March, 1980. One of the joint programs defined at the workshop was this "Energy Storage Market Penetration Evaluation" which will identify and evaluate potential improvements which are possible with the utilization of energy storage in USAF ground power applications.

APPROACH

Since it is not possible to analyze every USAF ground application, we would like to first identify several applications which are typical and where energy storage appears to have the potential to benefit the application's operational characteristics. These "typical" applications will be identified by analyzing the energy consumption characteristics of USAF applications over the past five years. This preliminary application identification will then be followed by an in-depth characterization of the identified applications. This will include an analysis of the electrical loading profiles with an analysis of the heating and air conditioning cycles as a function of climate. With these detailed characterizations, the applicability and benefits of various energy storage systems will be determined. We are accomplishing this by developing a data base on energy storage systems for military applications. This data base will include an extensive range of thermal and electrochemical energy storage systems and includes each of the parameters listed in Table 1 for the years 1980 to 2000. With the

TABLE 1

Storage Parameters

efficiency
reliability
survivability
service life
maintenance
operation
charge/discharge rates
dimensions, size, volume
mass, weight
materials availability
acquisition cost
life cycle cost
energy density
operational and environmental constraints

typical applications and the energy storage data base, the next step will be an iterative process to determine the optimum size and type energy storage system(s) for each application. To aid in accomplishing this, we have developed a "Multiple Criteria Decision Model" to compare the various systems and sizes. Once the optimum system has been determined, the obtainable benefits will be determined and research and development needs will be identified.

The section of this project which is nearing completion is the computer software, the "Multiple Criteria Decision Model". This is a generalized computer model which uses a number of variable decision criteria and a decision maker's evaluation of the relative importance of each of these criteria to select a preferred course of action. The model user is able to input the criteria that would affect the decision and is able to rate these criteria according to the decision maker's perceived importance of each. The input to the model includes the systems to be compared, optional first and second level subsystems, the criteria for judging these systems, a rating of the relative importance of each of the criteria, and data to evaluate the systems (or subsystems) for each of the criteria. For example, the systems may be energy storage systems which the model user desires to compare, or the systems could be "total energy systems" comprised of a generator or utility grid interfacing with various energy storage systems. If the decision maker wants to evaluate a number of systems for a range of sizes, size may be a subsystem. Using similar methodology, time may be a subsystem, or size may be a first level subsystem and time a second level subsystem; for example, an evaluation of competing systems could be accomplished for 5kW in 1980, 10kW in 1980, 5kW in 1990, 10kW in 1990, etc. The criteria in this case could be operational and cost parameters such as reliability and life cycle cost. For this project, the "USAF Energy Storage Market Penetration Evaluation", we will be comparing "total energy systems" for a range of sizes, a time span from 1980 to 2000, and the parameters listed in Table 1 (as the criteria). This will enable the determination of the optimum size and type energy storage system for each application. The output of the Multiple Criteria Decision Model" is presented in tabular output with a "system value" for each system (or first level subsystems when they exist). The system value is a value between 0 and 1 calculated by the model which takes into account all of the input for each system or subsystem. The system or subsystem which then has the highest calculated system value is the best system for the specified comparison. It should be noted that the criteria ratings are usually application dependent, and changes in these ratings can cause major changes in the system values. For those cases involving a range of time, which accounts for anticipated future system improvements, the model software provides a graphical output of time vs. system value for each system or subsystem. An example of this is shown in Figure 1. This program should provide a valuable aid in the decision making process.

SUMMARY

This project is the first comprehensive analysis of the use of energy storage in a ground power military market. The results will include the quantifiable benefits which USAF can realize with the utilization of energy storage systems as well as a projection of these benefits attainable over the next twenty years. The project will identify USAF applications in which

Subsystem: Size A

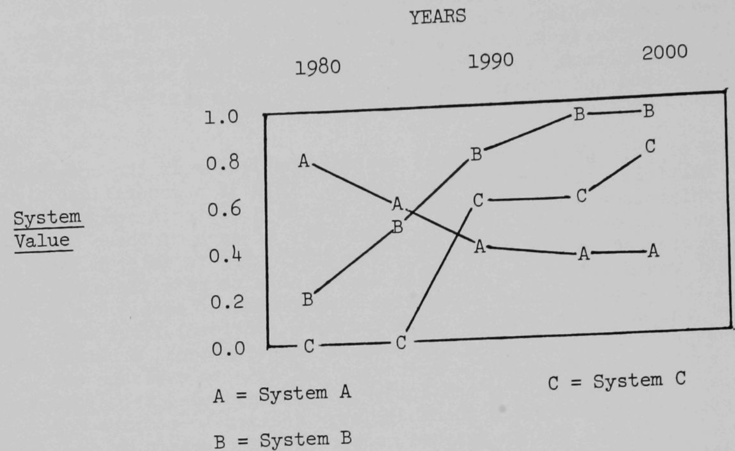

FIGURE 1

energy storage is advantageous. The areas in which additional research and development efforts will be most advantageous to USAF will also be identified within this project. Future plans in the energy storage area for the Terrestrial Energy Technology Program Office include work with energy storage for stand alone wind and solar energy systems, as well as research and development efforts identified by this project.

A HYDROGEN ENERGY CYCLE FOR ELECTRIC UTILITY APPLICATIONS

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ABSTRACT

The purpose of this study is to identify the economic, regulatory, safety, and environmental factors which are likely to have a major impact on the incorporation of a hydrogen energy cycle by the Niagara-Mohawk Power Corporation. It describes the Niagara-Mohawk electric/gas utility, and outlines two potential configurations for incorporating the hydrogen energy cycle in the utility's energy delivery system. The analysis also determined the break-even cost for a water electrolyzer, and the maximum economic length for a pure hydrogen pipeline. Other issues addressed are the compatibility of hydrogen with the utility's existing natural gas distribution system, the probable impact of existing safety codes, and the recent rulings of the New York Public Service Commission that are relevant to a hydrogen energy cycle. The report also quantifies the environmental impacts of solid polymer water electrolyzers and phosphoric acid fuel cells.

INTRODUCTION

The purpose of this study is to identify the economic, regulatory, institutional, safety, and environmental factors that are likely to have a significant impact on the implementation of a specific hydrogen project. The hydrogen energy cycle was selected for this analysis. It is an energy storage technology which enables electric utilities to increase the use of base-load power plants and consequently reduce the use of premium distillate oil. In a hydrogen energy cycle, hydrogen gas is produced by water electrolysis using inexpensive off-peak electricity from nuclear, hydroelectric, and coal-fired power plants. During peak-demand periods, the hydrogen gas is used to fuel generator plants which would otherwise burn expensive distillate oil. The generator plants can use conventional combustion turbines or fuel cells to convert the hydrogen into electrical energy.

A combined electric/gas utility company possesses characteristics that enhance the attractiveness of the hydrogen energy cycle. Such a company can avoid the cost of storing hydrogen gas by injecting the hydrogen directly into its gas pipelines, thereby supplementing its natural gas supply. The company could also construct special hydrogen pipelines along its existing pipeline rights-of-way in order to transport hydrogen from electrolyzers to fuel-cell power plants. Combined electric/gas utilities do not experience the inherent competition that exists between separate gas and electric companies which service the same geographical area.

The Niagara-Mohawk Power Corporation is a combined electric/gas utility company in New York State that was selected primarily because of its participation in hydrogen technology research and development. The corporation is involved in research and development programs directed toward utility applications of the General Electric Solid Polymer Electrolyte (SPE) Water Electrolyzer and the phosphoric acid fuel cell.

DESCRIPTION OF THE FACILITY

The Niagara-Mohawk Power Corporation (NMPC) serves a population of approximately 3.5 million people in northwestern New York. It has over 1.3 million electric customers and over 400,000 gas customers[1]. Some of the larger cities served by the utility are Albany, Schenectady, Troy, Buffalo, Syracuse, Niagara Falls, Oswego, Rome, and Saratoga.

The NMPC owns and leases approximately 5,000 MW of electrical generating capacity. Its power generation system includes the following types of plants:

- Nuclear (1 plant) — 630 MW
- Coal steam-turbine (2 plants) — 1,370 MW
- Oil steam-turbine (2 plants plus 30 percent share of a third) — 1,954 MW
- Combustion turbine (2 plants) — 360 MW
- Hydroelectric (76 plants) — 733 MW

Planned additions are an 850-MW coal-fired steam turbine in 1991, and a 41-percent share in an 1,100-MW nuclear power plant (an addition to the utility's existing Nine Mile Point Nuclear Power Plant). Locations of the major thermal power stations are shown in Figure 1, along with their capacity and type. In addition to its owned and leased facilities, NMPC has long-term contracts to purchase power from the Power Authority of the State of New York (PASNY). In 1979, approximately two-thirds of the total kWh sold by NMPC was generated by its own facilities, and one-third was purchased from PASNY and other utilities. Total electricity sales in 1979 were 33.3 billion kWh[1].

Niagara-Mohawk is part of the New York Power Pool. It buys and sells power to six other electric utilities. While the NMPC annual peak-load hours occur in December, the peak-load hours of most of the other utilities in the New York Power Pool occur in the summer. Each electric utility in the Pool is required to maintain an installed generating capability reserve of at least 18 percent of its forecasted annual peak load[2].

The natural gas system operated by NMPC contains 91 miles of transmission pipeline, and 5,728 miles of distribution line. The utility purchases gas from the Consolidated Gas Supply Corporation. In 1979, NMPC paid an average gas price of $2.00 per million Btu. Niagara-Mohawk sold 95 billion cubic feet of gas in 1978. Its gas purchase contract with Consolidated entitles NMPC to purchase up to 100 billion cubic feet per year; the current contract expires in 1990[3].

Niagara-Mohawk's R&D program ($16.4 million in 1980) is directed toward the goals of improving use of existing equipment and providing high-reliability energy delivery systems. The NMPC participates in the recently formed Fuel Cell Users Group, which is composed of 37 utilities, EPRI, DOE, and the Empire State Electric Energy Research and Development Authority. NMPC also is part of a joint program to evaluate the large-scale use of the General Electric Solid Polymer Electrolyte (SPE) Water Electrolyzer. The utility plans to demonstrate a 200-kW prototype SPE electrolyzer for producing hydrogen to cool its generators. Since 1974, NMPC has been investigating several alternatives for using hydrogen production and utilization technologies.

ECONOMIC ANALYSIS

There are two versions of the hydrogen energy cycle. One uses conventional combustion turbines, fueled with a mixture of natural gas and hydrogen, to generate electricity. The second version employs fuel cells to generate electricity. The first version, which will become commercially feasible for NMPC, uses electrolytically generated hydrogen to replace the distillate oil now being used to run the utility's combustion turbine peaking units. The electrolyzer would be powered by base-load generators during the time period (approximately 64 hours per week) when excess base-load capacity is available. In the proposed fuel cycle, the hydrogen would be blended with natural gas to a maximum of 5 percent hydrogen by volume, and transported through the utility's natural gas pipelines. An energy equivalent of the hydrogen produced would then be credited to the electric system for use by the combustion turbines during peak electrical demand periods. The combustion turbines would actually burn the methane/hydrogen (95/5) mixture.

The following break-even analysis determines the maximum allowable cost that the NMPC would be willing to pay for the water electrolyzer in the system described above. The analysis is based on the following assumptions:

- The cost to the utility of using base-load generator capacity which would otherwise be unused is only the variable cost (i.e., fuel, operation, and maintenance). In other words, capital charges are not made against electricity generated using "surplus" base-load capacity.

- Electrolyzer efficiency is 80 percent[4].
- Surplus base-load capacity is available 64 hours per week (8 hours each night plus an additional 8 hours on Sunday). See Figure 2 for the average winter weekly load curve.

Table 1 shows the current economic parameters provided by Niagara-Mohawk[3]:

TABLE 1. ECONOMIC PARAMETERS FOR NIAGARA-MOHAWK

	Current Fuel Costs, $\$/10^6$ Btu	Heat Rates, Btu/kWh	Operation and Maintenance Costs, Mills/kWh
Coal	1.56	9,000	4.5
Nuclear	.87	10,250	1.1
Combustion turbines	5.85	15,500	5.0

The annual fixed charge rate for generation equipment is 18.7 percent (includes depreciation, interest, taxes, and insurance)[2].

To determine the break-even cost, C, for the electrolyzer, the following equation is formulated:

$$\frac{C \times 0.187}{64 \text{ hrs/wk} \times 52 \text{ wks/yr}} + \frac{\$0.013/\text{kWh}}{0.80} = \frac{\$5.85/10^6\text{Btu}}{292 \text{ kWh}/10^6\text{Btu}} \qquad (1)$$

Solving, C =\$125/kWe

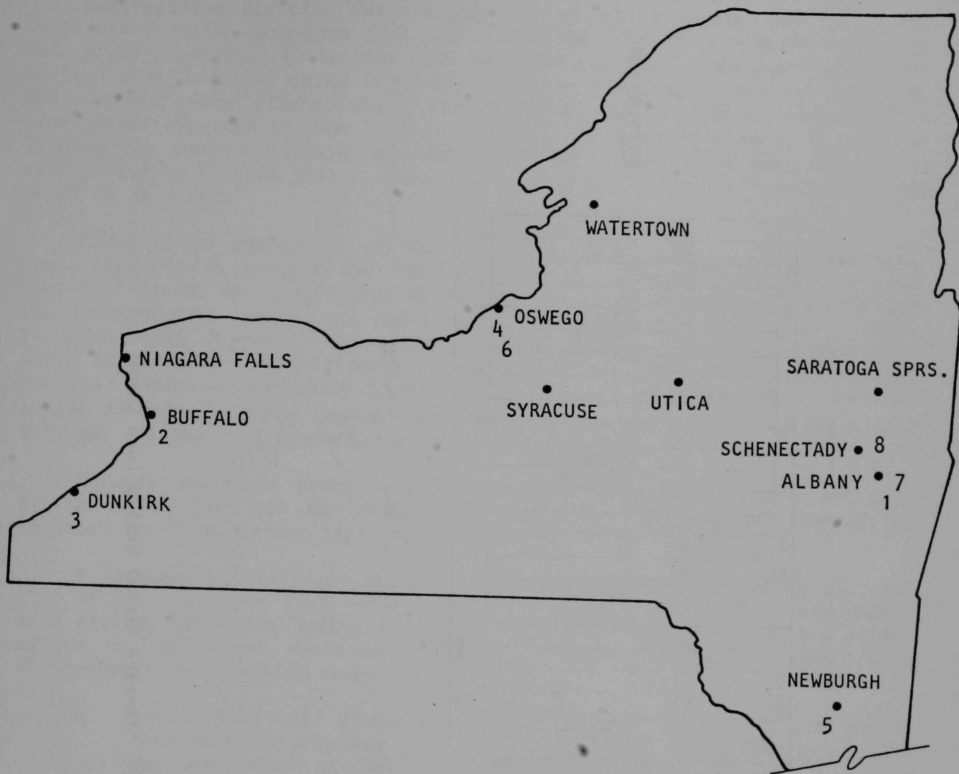
The first term is the capital charge per kWh for the electrolyzer. The second term is the marginal cost of off-peak base-load electricity divided by electrolyzer efficiency. Since surplus base-load capacity is two-thirds coal and one-third nuclear, this cost is the weighted sum. Marginal cost of electricity in \$/kWh is computed by the expression:

Marginal (\$/kWh) =

$$\text{Fuel cost } (\$/10^6 \text{ Btu}) \times \text{Heat Rate } (10^6\text{Btu/kWh}) + \text{O\&M cost } (\$/\text{kWh}) \qquad (2)$$

For current fuel prices, the break-even cost for the electrolyzer is \$125/kWe. The break-even cost increases by \$97/kWe for every dollar increase in the price of distillate oil. General Electric Corporation has indicated that the installed cost of its SPE electrolyzer in multi-megawatt capacity would be approximately \$200/kWe, using present technology. The GE goal is \$150/kWe[4]. The utility's two combustion turbine stations used 470,000 x 10^6 Btu of fuel in 1976. To displace this quantity, the electrolyzer capacity would be 52 MWe (assuming 64 hr/wk operation).

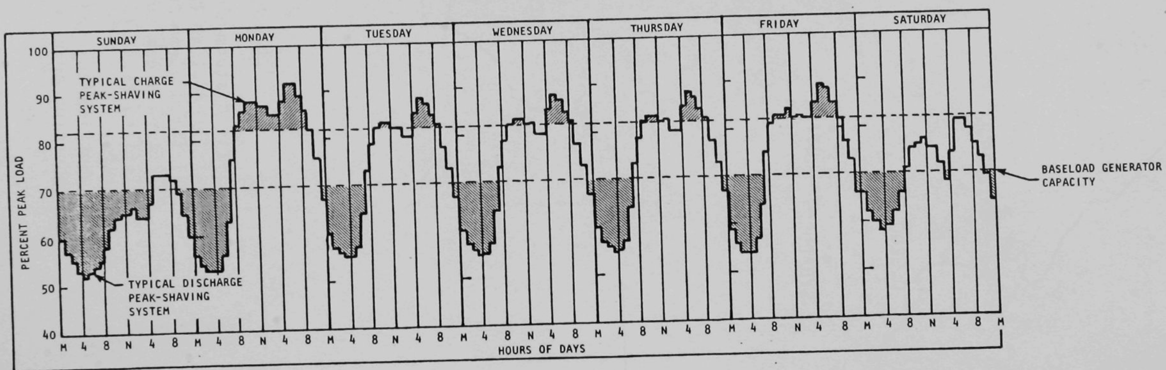
The second version of the hydrogen energy cycle incorporates fuel cells for generating electric power. The phosphoric-acid fuel cell (PAFC) will be the first type to be used on a commercial basis by utilities and industries. The technology is expected to be commercialized between 1983 and 1985. A 4.8 MWe demonstration PAFC power plant is now under construction in New York City.



Key:

	Plant	Capacity (MW)	Type
1	Albany Station	400	Oil-fired steam turbine
2	Charles R. Ituntley	788	Coal-fired steam turbine
3	Dunkirk	585	Coal-fired steam turbine
4	Oswego	1,200	Oil-fired steam turbine
5	Roseton	360	Oil-fired steam turbine
6	Nine Mile Point	610	Nuclear
7	Albany	180	Combustion turbine
8	Rotterdam	180	Combustion turbine

Figure 1. Niagara-Mohawk Thermal Power Plants



Source: Fernandes, 1974.

Figure 2. Average Winter Weekly Load Curve

Westinghouse Electric Corporation, one of the companies that plans to manufacture PAFCs, projects that the installed cost of a 6.9 MWe capacity PAFC power plant will be between $500 and $650 per kWe[5]. Their projected installed cost compares quite favorably with the projected costs for new coal and nuclear power plants, which are $1,100/kW and $1,850/kW, respectively (for plants expected to come on-line in 1987). However, the expected service life of the fuel-cell stack, representing about a quarter of the plant cost, is expected to be five years. Coal and nuclear plants have life expectancies of 20 to 30 years.

Three basic components of the fuel-cell power plant will be the fuel processors, which convert the fuel (natural gas or coal) to hydrogen; the fuel-cell stack, which generates direct current by electrochemically reacting the hydrogen with oxygen; and the inverter, which converts the direct current to alternating current. While the cost per unit capacity of the fuel-cell stack and inverter is relatively insensitive to the size of the power plant, the fuel processor subsystem shows significant economies of scale. For example, the cost per kWe capacity of a 10 MWe fuel processor is approximately $250/kW; a 1 MWe fuel processor would cost about $700/kW[5].

Because fuel-cell power plants are relatively pollution-free and make little noise, they can be located within populated areas, thus eliminating the need for transmission lines, and reducing distribution costs.

A combined electric/gas utility company will likely be one of the earlier utility users of fuel cells operated on natural gas. If Niagara-Mohawk were already producing hydrogen, it is likely that the following two alternative configurations would be considered for introducing fuel cells into their energy distribution network:

- Locate fuel-cell power plants near natural gas lines, and supply them with the pipeline gas. The power plants would have to contain fuel processors to convert the natural gas/hydrogen blend into pure hydrogen.

- Construct a hydrogen pipeline along an existing natural gas pipeline right-of-way, connecting the electrolyzer with each fuel cell. Rather than blending hydrogen with natural gas, transport pure hydrogen through the special pipeline. This alternative eliminates the need for fuel processors, since the fuel-cell stack would be supplied with pure hydrogen.

The second alternative appears most promising for smaller fuel-cell plants (i.e., 1 MWe capacity) because of the high cost of small fuel processors. If such plants are located within 14 miles of an electrolyzer, the cost of the hydrogen pipeline would be less than the cost of a fuel processor. This finding is based on an assumed pipeline cost of $10 per linear foot, installed[6].

In the second configuration, the hydrogen pipeline pressure would be allowed to vary so that the internal volume of pipe could be used to store gaseous hydrogen - a method of energy storage termed "line-pack." Thus, the operation of the fuel cell could be made independent of the operating schedule of the electrolyzer supplying hydrogen to the pipeline.

DISTRIBUTION AND UTILIZATION EQUIPMENT

An important consideration in the first phase of the Niagara-Mohawk hydrogen program is the compatibility of hydrogen gas with existing natural gas pipelines, compressors, regulators, and gas appliances. Several gas utilities have experience with distributing mixtures of hydrogen and methane. GASCO, a gas utility in Honolulu, Hawaii, distributes a mixture consisting of 90 volume percent methane and 10 volume percent hydrogen. There have been no problems with normal gas appliances. Public Service Electric and Gas Company (Newark, New Jersey) has determined that present appliance burners are satisfactory for a mixture consisting of 80 volume percent natural gas and 20 volume percent hydrogen[7].

The Institute for Gas Technology in Chicago has been evaluating the performance of natural gas distribution components, such as meters, regulators, valves, and couplings, when operated using hydrogen. A short-term experiment has shown that conventional natural gas distribution equipment is suitable for hydrogen, with the exception of certain lubricants and adhesives. Pipeline embrittlement, a concern with iron and steel pipes carrying pure hydrogen at very high pressures (above 1,000 psi) would not be a problem in the distribution of mixed gas. (The maximum distribution gas pressure at Niagara-Mohawk is 250 psi.) While the volumetric leakage rate for hydrogen is roughly three times that for natural gas, the energy loss rate is roughly equivalent. Hydrogen does leak at significantly faster rates through plastic pipe, however. Its permeability through polyethylene pipe is five times that of methane. PVC II and acrylonitrate-butadiene pipe materials would not be suitable for hydrogen gas distribution since the hydrogen permeability rate through these materials is between 60 and 80 times that of steel pipe. Plastic, rubber, and organic seals may also present a problem due to the heat release that accompanies the expansion of hydrogen gas between high transmission line pressure and lower distribution main pressure[8].

At common gas distribution line pressures (approximately 100 psig), the rate of energy transport for a given length of pipe would be about the same for hydrogen and natural gas. This is because hydrogen is lower in density and viscosity, which allows for increased flow rate under laminar conditions. This compensates for hydrogen's lower volumetric energy density (one-third that of natural gas).

REFERENCES

1. Niagara-Mohawk Power Corporation - Annual Report for 1979.

2. Fernandes, R.A. "Hydrogen Cycle Peak-Showing for Electric Utilities," in Proceedings of the Ninth Intersociety Energy Conversion Engineering Conference, 1974.

3. Niagara-Mohawk Power Corporation - Form 10-K, filed with the Securities and Exchange Commission.

4. Russel, J.H. "Development of Solid Polymer Electrolyte Water Electrolysis for Large Scale Hydrogen Generation," in Proceedings of the DOE Chemical Energy Storage, February 1980.

5. Personal Communication with Dave Pouchot and J.R. Lauce, Advanced Energy Systems Division, Westinghouse Electric Corporation, November 7, 1980.

6. The 1979 Dodge Manual for Building Construction Pricing and Scheduling, McGraw-Hill.

7. Kelley, J.H., and R. Hagler. "Storage, Transmission and Distribution of Hydrogen," in The International Journal of Hydrogen Energy, Vol. 5, No. 1, March 1980.

8. Jasionowski, W.J., and H.D. Huang. "Study of the Behaviour of Gas Distribution in Hydrogen Service," in Proceedings of the DOE Chemical Energy Storage and Hydrogen Energy Systems Contracts Review, February 1980.

BIBLIOGRAPHY

Burger, J.B. "An Energy Utility Company's View of Hydrogen Energy," in International Journal of Hydrogen Energy, 1976, Vol. I, pp 55-64.

Casazza, John A. "What Can Hydrogen Do for an Energy Company," in Combustion, May 1976.

Cox, K.E., and K.D. Williamson. Hydrogen: Its Technology and Implications, CRC Press, 1977.

Electric World Dictionary, 1978.

Gregory, Derek P. A Hydrogen Energy System, The American Gas Association, 1972.

Guerra, C.R., J.E. Griffith, K. Kelton, and D.C. Nielsen. "Natural Gas Supplementation with Hydrogen," in Proceedings of the DOE Chemical/Hydrogen Energy Systems Contractor Review, August 1978 (CONF-771131).

Lotker, Michael. "Hydrogen for the Electric Utilities - Long Range Possibilities," in Proceedings of Ninth Intersociety Energy Conversion Conference, 1974.

The Market Potential for Electrolytic Hydrogen, Electric Power Research Institute, EM-1154, May 1979.

Mathis, David. Hydrogen Technology for Energy, Noyes Data Corporation, 1976.

National Association of Regulatory Utility Commissioners, 1977 Annual Report on Utility and Carrier Regulation, ed. G. Beierlein, 1978.

Smalley, W.M. Environmental Analysis and Assessment of Selected Hydrogen Production and Storage Systems, U.S. Department of Energy No. ATR-80 (7788-02)-1, October 1979.

Smith, W. Davis, and Joseph Santangelo. Hydrogen: Production and Marketing, American Chemical Society Symposium Series 116, 1980.

Steinmetz, G.F. "Hydrogen as a Mid-term Gaseous Fuel Supplement by Blending with Natural Gas," in Proceedings of the DOE Chemical/Hydrogen Energy Systems Contractor Review, August 1978.

SURVEY OF COMMERCIAL THERMAL STORAGE INSTALLATIONS IN THE UNITED STATES AND CANADA

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ABSTRACT

Nearly 300 thermal energy storage installations in the United States and Canada were identified by a mail and telephone survey conducted by the Franklin Research Center. Information was obtained on approximately 220 installations. For 175 installations of hot, cold and combination hot/cold storage, sufficient quantities of technical information was obtained to warrant inclusion in this report. Water is the most prevalent medium of energy storage. Although almost all respondents indicated satisfaction with the performance of their storage systems, hardly any could provide detailed performance records. Operational and construction cost data were either unobtainable or are not sufficiently well specified to be useful. The project is continuing in two phases: publication of the survey data by ASHRAE, and detailed descriptions, performance, and cost data for a few representative installations.

1. SCOPE

A survey of commercial thermal energy storage installations in the United States and Canada was undertaken by the Franklin Research Center (FRC) on behalf of the U.S. Department of Energy acting through the Oak Ridge, TN facility of the Union Carbide Corporation. Mr. James Martin was the Project Monitor.

The survey was to include both heat and cold storage projects but was to exclude experimental systems and domestic water storage, storage primarily serving solar energy, and storage in one- and two-family homes. Off-peak ice storage used in churches, dairies, and breweries was also excluded from the survey. No site visits were undertaken.

2. OBJECTIVE

Many people consider thermal energy storage to be in an experimental stage. To show that this is no longer the case, this survey was undertaken and will be published for the benefit of design professionals, building owners and operators, and utility personnel. It provides locations of thermal storage installations, system details, and information about their performance. The names, addresses, and telephone numbers of persons familiar with each installation are also given for the benefit of those who wish to obtain additional information.

The purpose of this survey is to document the extent of thermal storage application, its reliability, and its versatility. It is hoped that it provides useful examples of successfully executed projects, and that it will induce others to apply thermal storage under suitable conditions.

3. PROCEDURE

3.1 Methodology

The Thermal Energy Storage survey was divided into four distinct tasks. The first task was the briefing of information specialists on the topic of thermal storage. The second task was the collection by those specialists of information on thermal storage throughout the United States and Canada. The third task consisted of evaluating the collected information for technical accuracy, validity, and completeness. Included in this task was a review by an ASHRAE Thermal Energy Storage Technical Evaluating Committee. The final task was the editing of the information gathered and the preparation of a report.

3.2 Information Sources

Potential information sources were obtained in several ways. Thermal storage projects and design engineers who had designed and/or built thermal storage systems and were known to FRC personnel through their activities of long standing in the thermal storage area. The Project Manager, in his capacity as the founder and chairman of the ASHRAE Technical Committee on Thermal Storage, was familiar with engineers throughout the HVAC industry and with electric utility personnel who had an interest in the subject. Several volumes of the Survey of Utility Load Management and Energy Conservation Projects[1,2] were used to identify electric utilities that had been and are active in promoting thermal storage. The Electric Power Research Institute and the Edison Electric Institute were also contacted to supplement this list.

A survey on chilled water storage facilities had been undertaken on behalf of the Southern California Edison Company by Marx Ayres Associates,[3] and the results of that survey were made available to this project. Manufacturers of thermal storage devices also provided leads to a number of projects. In most cases, even when an initial contact did not yield directly usable information, the person contacted would provide one or more leads which eventually provided information on storage projects.

3.3 Telephone Calls

The bulk of the information was obtained by telephone or through questionnaires sent to follow up phone calls. "Cold" mail questionnaires were found to be useless. In many cases the initial phone call was sufficient to obtain the required information. In other cases, follow-up calls were required. Although multiple follow-up calls were unusual, some were necessary. These calls, however, were usually positively received, and the information was eventually supplied. In cases when the individual contacted could not immediately make the time available to answer all questions, a follow-up call was made, or a letter including copies of the survey form was sent. Information regarding contacts for additional sites was always encouraged. Frequently, individuals contacted about one project knew of additional sites and/or had knowledge of other engineers who had executed thermal storage projects. These leads were then followed up.

3.4 Quantity of Contacts

In most cases, a number of telephone calls was required before reaching the person who had the information desired. Thus, the total number of telephone calls made for this survey is approximately one-thousand.

In addition to the letters previously described, a thank-you note was mailed to all respondents who replied in writing. The total number of letters written is approximately one-hundred and fifty.

3.5 Proposed Publication

It is planned to have the results of the thermal storage survey published by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) in a special document. The society expressed its willingness to do so provided ASHRAE had some inputs to the contents and format of the document. This input was obtained through a three-member ASHRAE Review Committee which met twice with FRC personnel and made recommendations that are being carried out. Publication is planned for later in the year (1981).

4. RESULTS

4.1 Overview

Close to 300 installations in the United States and Canada have been identified. It is believed that this covers between 50% and 90% of all installations that actually exist in that area. Some technical information was obtained on 220 installations. Sufficient information to be included in the proposed publication is available for 175 at the present time.

4.2 Performance

The overwhelming majority of the thermal storage installations identified perform satisfactorily. Less than five percent of the respondents indicated significant problems, such as the break of an electrical cable embedded in a concrete floor, excessive thermal response time, lack of set-point temperature stability. However, documented performance records are virtually non-existant.

In the majority of cases, the owners or designers merely indicated their estimates or their opinions as to the performance of the systems without having any measured data to back up their claims. Only a handful of operators were able to quantify the actual energy impact which thermal storage has upon overall performance of their systems.

The performance of the retrofit systems was equally satisfactory, according to the owners' reports. Unfortunately, the majority of the retrofit systems were introduced in connection with a modification or enlargement of the original installation; therefore, a simple comparison between "before" and "after" energy consumption or cost data is not possible.

4.3 Geography and Storage Type

Of the 175 installations included in this first report, 58% were heat storage systems, 23% were cold storage systems, and 19% were combined heat and cold thermal storage systems. A summary of system application by geographic regions is shown in Table 1.

Table 1. Geographic Distribution of System Application

Region	Heat Storage	Cold Storage	Heat and Cold Storage	Total
United States				
Northeast	38	6	17	61
Northwest	0	0	1	1
Southeast	10	2	3	15
Southwest	4	15	1	20
Midwest	28	7	9	44
Canada	21	10	3	34
TOTAL	101	40	34	175

The table shows that:

- Heat storage predominates in the East, the Midwest and Canada,
- Cold storage predominates in the Southwest,
- The Northeast has a relatively high degree of combination heat and cold storage systems,
- Storage is virtually non-existant in the Northwest.

The preferred storage medium for hot storage is water (62%) followed by sand (29%), and brick and concrete (9%). Two-thirds of the water storage installations use pressurized water with the storage temperature above 100°C. In the United States, ice is the preferred storage medium over chilled water by 2:1, but no ice storage installations at all were found in Canada. Water predominates (82%) in the combined heat and cold storage installations; a few US installations use the sensible heat of water for heat storage and the latent heat of the water/ice transformation for cold storage.

A breakdown by storage medium, storage system, and country is given in Table 2. Only further investigations will allow a definitive analysis of whether this apparent trend in thermal storage system type and distribution is due to basic geographic climatic considerations or is entangled in rate structures, industrial distribution, and other economic considerations.

Table 2. Storage Media and Systems by Country

Storage Type	United States	Canada	Total
HEAT STORAGE			
Pressurized Water (> 100°C)	27	15	42
Unpressurized Water (< 100°C)	16	5	21
Sand	29	0	29
Concrete, Brick	8	1	9
COLD STORAGE			
Water	10	10	20
Ice	20	0	20
COMBINED HEAT AND COLD STORAGE			
Water	25	3	28
Water/Ice*	6	0	6
TOTAL	141	34	175

*Water is used for heat storage, ice for cold storage

4.4 Incentives for Thermal Storage

As a part of the investigation, the respondents were asked their reasons for installing thermal storage systems. Their responses are shown in Table 3.

Table 3. Stated Reasons for Installing Thermal Storage Systems

Region	Peak Demand Reduction	Offpeak Rates
United States		
Northeast	36	23
Northwest	1	0
Southeast	12	1
Southwest	20	0
Midwest	25	16
Canada	34	0
TOTAL	128	40

Demand reduction offers the most obvious and financially attractive incentive for substantial cost savings. Since demand charges are levied for at least the length of the billing period and, in many cases, for the better part of a year (demand ratchet tariffs) even though the duration of that peak demand may be relatively short, the use of thermal storage to reduce these peaks is highly beneficial.

Thermal storage by consumers may allow a utility to postpone or eliminate the construction of new power plants. Thus, its widespread use would be particularly beneficial to utilities whose peaks show a high growth rate.

4.5 Marketing

Marketing of thermal storage systems involves the electric utility as a prime actor with manufacturers and design engineers as secondary actors. All of them are needed, however, if the promise of conservation through thermal energy storage is to be fulfilled. An aggressive marketing campaign by a manufacturer can have a significant impact on the utility and, in some cases, on its policies if the economics are favorable to thermal storage. Suitable rate structures as well as the availability of utility staff and support can provide a marketing impetus to thermal storage systems that is beneficial to the utility and its customers.

In general, electric utilities are the prime movers in the application of thermal storage. They make its use economical and attractive through proper rate structures. This is apparent from the survey which shows concentrations of thermal storage installations in the service areas of certain utilities, while no thermal storage is used in neighboring utility service area with, presumably, similar environmental conditions.

5. CONCLUSIONS

The majority of building owners and operators are highly satisfied with their thermal storage systems, although few are able to provide hard data to back up their "gut feelings." The operational performance of thermal storage devices is excellent; very few cases of unsatisfactory operation were reported.

The reduction of peak demand is the preponderant reason for installing thermal storage. Lower off-peak energy rates are the reason in only 20% of the installations. Electric utilities provide the major impetus to the installation of thermal storage. One should therefore look to the electric utility industry as the major vehicle for wider use of thermal storage.

There exists a large quantity of qualitative performance data, but very few quantitative performance and cost data. The performance of thermal storage installations is rarely monitored because monitoring appears as an unnecessary expense to the building operator. If reliable, long-term performance data are desired, an outside agency must inaugurate a separate program to that effect.

Financial information on thermal storage projects is frequently unavailable because neither the designer nor the owner has bothered to collect the data required. A separate effort is needed to elicit this. What is desired is a sufficiently detailed breakdown of equipment cost so that the incremental cost of thermal storage can be determined.

6. RECOMMENDATIONS

A detailed investigation should be conducted on a limited number of sites with stress on design parameters, performance results, cost breakdowns and economic impact on users and utilities. Concentrating on this smaller number of sites will result in detailed project descriptions and accurate cost information which would prove highly useful to potential users of thermal storage. This limited number (say six to ten) of installations should be selected so that a variety of system types, applications, climates, and electric utilities are covered. Both new and retrofit installations should be included.

A design procedure for thermal storage installations should be developed.

A methodology for determining the suitability of thermal storage to a particular application should be developed. This methodology should include technical as well as financial consideration and criteria.

Methodologies should be developed for optimizing thermal storage systems with respect to various parameters, such as lowest peak load, least energy consumption, least energy consumption during peak hours.

7. ACKNOWLEDGEMENT

The author is indebted to Mr. Donald Geistert of the Southern California Edison Company for permission to use the data from Reference 3 before publication.

8. REFERENCES

1. Survey of Utility Load Management and Energy Conservation Projects, 1st Revised Report, EUS, Inc., December 1978, ORNL/Sub-77/13509/4.

2. Survey of Utility Load Management and Energy Conservation Projects, 2nd Revised Report, EUS, Inc., November 1979, ORNL/Sub-77/13509/5.

3. A Guide for Off-peak Cooling of Buildings, Southern California Edison Company, September 1980.

SESSION IV:
STORAGE FOR TRANSPORTATION

APPLICATION ANALYSIS OF ENERGY STORAGE SYSTEMS FOR TRANSPORTATION

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ABSTRACT*

An application analysis study of energy storage systems for automotive propulsion was conducted over a period of four years. The purpose was to identify the most promising energy storage devices and the vehicular missions for which the resultant propulsion systems are best suited. Projected costs of the vehicles are used to discuss the study's findings. Additionally, some preliminary findings concerning an assessment of the impact on energy storage device requirements of current transportation developments and trends are discussed.

INTRODUCTION

For a number of years we have been conducting application analysis studies addressing the prospects for energy storage devices and energy storage propulsion systems as alternatives to current petroleum consuming transportation systems. Several years ago, we completed a study concerning the use of energy storage systems for non-highway applications[1]. For the last four years, we have been assessing the prospects for using energy storage systems in automobile propulsion systems[2], and we are now assessing the impact on energy storage device requirements of current transportation developments and trends. This paper will address the latter two issues.

Because our transportation network, our economy, and our very social structure is vulnerable to embargo and petroleum shortages, the Office of Energy Systems, R&D, U.S. Department of Energy, initiated a study in late 1976

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to examine various energy-storage devices and their appropriate propulsion systems as possible alternatives to the petroleum-fueled internal combustion engine (ICE) propulsion systems. Although other researchers and analysts evaluated individual energy-storage devices and power systems, it is hard to find in their work a common basis for comparison. Realizing this, we examined a wide range of energy-storage systems and evaluated the relative performance, mass, and cost of each, using standardized guidelines and procedures to facilitate comparison.

The study was a Department of Energy multi-Laboratory effort managed by Lawrence Livermore National Laboratory (LLNL). A study team drew personnel from five DOE Laboratories and divided them into five panels. The Laboratories represented were:

- Argonne National Laboratory
- Battelle Pacific Northwest Laboratory
- Brookhaven National Laboratory
- Lawrence Berkeley Laboratory
- Lawrence Livermore National Laboratory.

Four of the panels investigated energy-storage technologies. The Electrochemical Panel, chaired by Argonne National Laboratory (ANL), examined batteries; the Mechanical Panel, chaired by Battelle Pacific Northwest Laboratory (BPNL), evaluated mechanical-energy-storage devices; the Chemical Panel, chaired by Brookhaven National Laboratory (BNL), examined hydrogen systems; and the Thermal Panel, chaired by ANL, evaluated this technology. The fifth panel, the Automotive End-Use Panel was chaired by LLNL. It investigated the suitability of energy-storage devices for future automotive propulsion. These panels were staffed by more than 65 individuals from DOE Laboratories, NASA, 14 different industrial firms, and four universities. While each panel defined its own criteria, methodology, and procedures for data collection, all worked closely together.

ANALYTICAL APPROACH

Each investigative panel assessed the performance characteristics of future energy-storage devices, determined the likelihood of overcoming technical barriers, and identified the research and development tasks to be accomplished for successful development.

The projected characteristics of future energy-storage devices are uncertain, and that degree of uncertainty is important. So, using decision-analysis techniques, these characteristics were defined not only as a function of time but also of the likelihood of attainment expressed simply as Probable, meaning reasonable expectation of being achieved, or Optimistic, meaning unlikely to be achieved and, therefore, representing an upper limit for the technology.

The Automotive End-Use Panel established four performance criteria: (1) performance equivalent to today's internal combustion engine (ICE) automobile (that expected of a general-purpose automobile), (2) performance needed for a limited-range urban vehicle, (3) performance midway between the two, and (4) minimum usable performance. These performance levels shown on Table 1 were defined in terms of both acceleration, with power-to-mass ratio as a surrogate, and range with acceleration capability maintained to the 80% discharge level of the energy-storage devices or to the 80% depletion level of other energy supplies. For each performance category, four vehicle sizes were defined: 2-passenger, 4-passenger, 5-passenger and multipurpose vehicles. Therefore, 16 distinct vehicles were defined encompassing a wide spectrum of automobile types. In addition, the study considered three time periods: 1980-1985, 1985-1990 and 1990-2000.

In conducting the analysis, the calculated characteristics of ICE automobiles in each size/performance category were used as a baseline for comparison. Then we conceptually replaced the ICE propulsion system of each vehicle with an energy-storage propulsion system to provide the same vehicular performance. The calculated vehicle mass, size, energy use, and cost (as a function of the likelihood of attainment and the three time periods) represented the suitability of each energy-storage device and propulsion system in each type of vehicle.

Table 1. Performance level requirements.

Performance	Range[a]		Power-to-mass ratio[b]		Approximate full-power acceleration time (s)	
	km	(mi)	kW/kg	(hp/lb)	0-48 km/h (0-30 mph)	0-97 km/h (0-60 mph)
Equivalent	400	(250[c])	0.049	(0.03)	4.7	14.8
Intermediate	240	(150)	0.033	(0/02)	6.8	20.4
Limited	120	(75)	0.026	(0.016)	8.4	24.3
Minimum	80	(50)	0.016	(0.01)	13.2	35.1

[a] Range determined at 80% fuel usage or 80% storage device discharge.

[b] Power measured at input to transmission, mass is curb mass plus a test mass of 136 kg (300 lb).

[c] Includes rapid (5-15 min) refueling or recharging requirement.

ENERGY-STORAGE DEVICES

There are many potential candidate electrochemical systems for electric vehicle applications. From an original list of about 30 evolved a set of eight (8) as the most promising candidates. For ease in comparing them, they were divided into three groups: engineering, advanced, and exploratory.

During this study, characteristics of the various systems were continually updated because of ongoing R&D and testing programs. In addition, there were improvements in the evaluation techniques. The Probable projections shown in Table 2 are the result of the evaluation.

For all generic battery systems, there are design tradeoffs to be made between short-term peak-power capacity and battery energy content. The Electrochemical Panel projected the relationship between short-term

Table 2. Forecasts for batteries.

Battery type	Time[a] period	Prob. level	$E_{C/3}$,[b] Wh/kg	$E_{C/5}$,[b] Wh/kg	P_{M80},[c] W/kg	Cost[d] $/kg	Service Life, Years
			Engineering Stage				
Pb/acid	1	Probable	42	58	66	3.00	3
	2	Probable	46	53	95	2.76	4
	3	Probable	49	56	98	2.69	5
Ni/Fe	1	Probable	55	59	102	6.86	10
	2	Probable	60	64	112	5.05	10
	3	Probable	65	70	130	4.81	10
Ni/Zn	1	Probable	70	74	125	9.22	2
	2	Probable	76	80	135	6.17	4
	3	Probable	80	86	140	5.27	5
			Advanced Stage				
Na/S(cer)	2	Probable	90	105	100	5.42	2
	3	Probable	108	125	120	5.20	3
Zn/Cl_2	1	Probable	90	95	95	10.83	3
	2	Probable	98	104	115	8.05	4
	3	Probable	105	111	120	6.31	5
Li/FeS_2	2	Probable	110	128	115	9.42	4
	3	Probable	120	140	130	7.21	5
			Exploratory Stage				
NaS(glass)	2	Probable	112	114	180	6.37	2.5
	3	Probable	118	120	200	4.23	5.0

[a] 1--1980-1985, 2--1985-1990, 3--1990-2000

[b] Specific energy at 3-h (5-h) discharge rate. The 3-h rate is the normal rate at which a battery's specific energy is measured and the 5-h rate is used during the end-use analysis in the optimization process.

[c] Specific peak power when 80% discharged.

[d] 1977 dollars, since specific energy can be adjusted, cost per unit weight is important.

(15- to 30-s) specific peak-power at the 80% discharge point (P_{M80}) and specific energy at the 3-h discharge rate ($E_{C/3}$) for each battery type. This relationship was used in a procedure developed by Automotive End-Use Panel to optimize the battery characteristics to the particular vehicle performance level. In effect, the battery was optimized so that it simultaneously runs out of energy and peak-power capability at about the 80% discharge point. When this flexible approach is not used, the batteries may be overly large and costly because of inability to adjust their characteristics.

The Electrochemical Panel also made projections of size effects on specific energy. This was considered in the End-Use Analysis. The specific energy of batteries decreases as capacity (size) is reduced. This effect does not scale linearly and is particularly important in the case of Zn/Cl_2 and the high-temperature batteries. These important relationships have not been included in EV modeling efforts until now.

Although the aluminum-air battery development started too late to be included in their projections, the Electrochemical Panel did state that the specific energy and rapid refueling capability are expected to make the aluminum-air battery the only electrochemical system with realistic prospects for achieving performance equivalent to gasoline-fueled vehicles.

Six types of mechanical-energy-storage devices were selected for evaluation. Linear-elastic solids, elastomers and liquid springs appear too impractical for automotive systems. Flywheels, compressed-air storage, and hydraulic accumulators appear practical but not as primary sources of propulsion energy (because of low specific energy). Flywheel systems have marginal energy densities and continuously lose energy but are good power-boosting devices. Compressed-air storage requires a source of thermal energy and would have to be used in combination with a heat source. Hydraulic accumulators have very low specific energy but could be useful in hybrid applications, since hydraulic components are well developed and reliable. The Probable projections for these mechanical energy-storage devices are given in Table 3.

Table 3. Forecasts for mechanical energy-storage devices

Storage Device	Time[a] Period	Probability Level	Specific Energy Wh/kg	Cost[b,c] $/kg
Isotropic [c] Flywheel	1	Probable	6.6	
	2	Probable	8.8	6.60
	3	Probable	11.0	
Composite [c] Flywheel	1	Probable	22.0	
	2	Probable	33.0	10.65
	3	Probable	48.0	
Compressed [d] Air	1	Probable	26.4	
	2	Probable	44.0	f
	3	Probable	33.0	
Hydraulic [e] Accumulator	1	Probable	3.5	
	2	Probable	4.8	f
	3	Probable	5.3	

[a] 1 - 1980 - 1985, 2 - 1985 - 1990, 3 - 1990 - 2000.

[b] 1977$.

[c] Includes motor housing and vacuum pump.

[d] Includes pressure vessel and air stored at 10.3×10^6 Pa.

[e] Includes pressure vessel with compressed gas.

[f] Costs of these devices were not calculated separately. Cost is sensitive to the power and energy required. In each case, the cost was made part of the vehicle cost analysis.

The energy-storage requirements for power-boosting are a small fraction of what would be required if the flywheel system were used as the principal source of energy. Both the isotropic and state-of-the- art fiber-composite type flywheel systems could improve the performance of vehicles. The choice will depend on their relative impact on the vehicle price, reliability and safety. Extensive analysis of these factors indicates that although the specific energy of the fiber-composite flywheel appears to be much higher than that for isotropic flywheels, the uncertainty in predicting their mechanical behavior at this time places them at a disadvantage. Given time and sufficient research funds, the fiber-composite flywheel may reach a level of development that would remove these uncertainties.

Chemical storage systems were constrained to systems using hydrogen. They differ from liquid-fuel systems because the fuel is stored as a chemical compound or is a cryogenic liquid that must be liberated by some process before it can be burned.

The hydrogen systems selected as most promising candidates were the liquid (cryogenic) hydrogen system, those using titanium and magnesium alloy hydrides, and a system which uses a bed of hollow glass microspheres filled with hydrogen at high pressure and discharged in a controlled fashion to supply hydrogen.

Liquid hydrogen systems place the hydrogen at its boiling temperature (-252°C) in insulated tanks. It is used as a gaseous fuel when pumped through a vaporizer. Iron titanium hydride ($FeTiH_x$) serves as a hydrogen carrier at ordinary temperatures and moderate pressures. Application of heat will release the hydrogen. The hydride of magnesium/nickel (10%) also stores hydrogen reversibly. The content of hydrogen is higher than for iron titanium (5.5%). The particular glass used for the glass microspheres, fills or releases hydrogen at high temperature and has a low permeability at low temperatures. The cost of these devices were not calculated separately but were included in the vehicle cost analysis. Table 4 gives the Probable projections for these hydrogen-storage devices.

Table 4. Projected specific energy and specific peak power at 80% discharge for hydrogen-storage devices.[a]

Storage device	Probability level	Specific energy (Wh/kg)			Specific peak power (80% discharge) (W/kg)		
		1980-85	1985-90	1990-2000	1980-85	1985-90	1990-2000
Liquid H_2	Probable	675	1080	1680	b	b	b
$FeTiH_x$	Probable	84	90	96	1100	1230	1320
MgH_x	Probable	105	144	165	870	1230	1380

[a] Heat content values have been converted to their mechanical equivalent using 30% efficiency.

[b] In this case, peak-power capacity is determined by heat engine.

Thermal storage systems which use materials capable of storing thermal energy in significant quantities, which are used to provide a pollution-free heat energy source for a Stirling engine or some other external heat engine for automotive propulsion, is intriguing. While a number of materials are candidates for this application, we chose lithium fluoride because it is an attractive thermal energy storage material for two reasons: it has a high energy density (approximately 0.5 kWh/kg,) and it releases its heat-of-fusion only 2°C below the maximum system temperature (1121 K), which permits a Stirling engine to operate very near its maximum efficiency. Since it is believed that these devices still need considerable research and development, we only believed them likely in the 1990-2000 time period if one made optimistic projections.

ENERGY STORAGE PROPULSION SYSTEMS

The Automotive End-Use Panel and the Energy-Storage Panels selected seven generic types of energy-storage propulsion systems to be analyzed:

- All-battery systems
- Battery/flywheel systems
- Dual-fueled hybrid systems
- Power-leveling hybrid systems
- Hydrogen-fueled ICE systems
- Hydrogen fuel-cell systems
- Thermal-storage/ICE systems

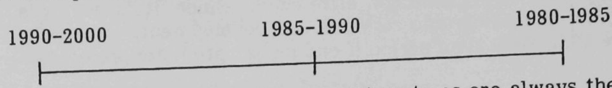
Mechanical storage devices were judged unsuitable as primary sources of propulsion and were limited to power leveling. The dual-fueled hybrid system is a minimum or limited-range battery/flywheel system for electric operation, and in addition, a small ICE is included for hybrid operation when vehicle range extension is required. The power-leveling hybrid systems permit analysis of the effect of mechanical storage devices and batteries employed to level ICE engine-power requirements. Two additional systems were examined to see if turbines are better than the Otto cycle engines for this application. These systems combine a turbine with a small power-boosting flywheel. The hydrogen-fueled ICE systems were similar to the basic ICE propulsion systems except for the fuel storage system and the characteristics of the hydrogen-fueled engine. The magnesium/nickel hydride system was combined with the iron titanium system (dual-hydride) to eliminate large start-up heat requirements. We also examined hydride-fueled fuel cell systems with a battery power booster. The thermal system employed a lithium fluoride heat source and a Stirling engine.

RESULTS AND CONCLUSIONS

Many energy-storage devices and automotive propulsion systems have been examined. Only a sample of the end-use analysis results are presented in this paper. They are for a five-passenger vehicle and the Probable case. Many other cases are given in reference 2, or they can be inspected through the Technology Information System (TIS) available through LLNL.

In discussing the study's results, it is useful to divide the energy storage propulsion systems into three categories according to purpose. These are: electricity utilization, alternative fuel utilization, and petroleum fuel economy improvement. As stated earlier, initial vehicle cost can and will be used as a parameter for comparing vehicles of equal performance.

Figure 1 indicates that energy storage propulsion systems designed to maximize the use of electricity will be able to achieve various performance levels. To interpret this figure and those that follow, please note that cost information is presented as a vertical tic mark or series of tic marks which relate to time periods of availability as follows:



For energy storage systems, the lowest cost systems are always the most remote time period. Since some storage devices were not projected as available in the first or sometimes second time period, their tic marks will be missing. Thus, a single tic mark represents the 1990-2000 period. For the ICE (Baseline) system, which is only presented as an equivalent performance automobile, the time periods are reversed since they are actually expected to increase in cost in the future.

An examination of Fig. 1 indicates that all energy storage automobiles will cost more than ICE systems and the cost difference will decrease with time. The dual-fueled hybrid (in this case 120 km electric range) will give an equivalent performance vehicle at about limited performance EV costs. If only minimum performance is required, no battery is a clear choice given the uncertainty of projections. As the performance requirements are increased, the more advanced batteries appear to have an advantage in the later time periods.

Figure 2 indicates that flywheels do not help in vehicles with low power requirements, but their importance increases particularly in the near term as power requirements are increased. It should be pointed out that the dual-fueled hybrid also utilizes a flywheel to allow the use of a smaller heat engine.

In the utilization of alternate fuels area, Fig. 3 indicates that hydrogen systems compare favorably with EVs. Table 5 presents a comparison of the power leveling hybrid results. These systems are designed to use energy storage devices to effect fuel economy improvements. They essentially all cost more than the baseline ICE. The life cycle costs (10 yrs and 160,000 km) are also for the most part higher than the ICE except for the turbine/flywheel systems. While fuel costs will be reduced, the reduction is not enough to overcome the higher initial cost in most cases.

The four-year study effort of Energy Storage Systems for Automobile Propulsion has led us to the following selected conclusions:

- Automotive energy-storage propulsion systems can be developed for various performance levels from general-purpose vehicles (ICE-equivalent), such as dual-fueled hybrids, power-leveling hybrids, and hydrogen systems, to specific mission vehicles, particularly battery/flywheel electrics and all-battery electrics.

- Of those few secondary battery systems selected for detailed evaluation, none can be projected as first choice for development, given the present state-of-the-art and uncertaintainties of future battery characteristics.

- All advanced energy-storage devices and vehicles are high-risk developments.

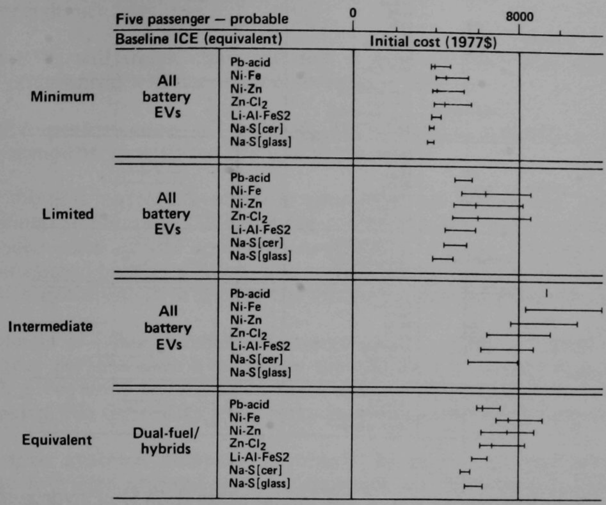


Fig. 1. Projected initial cost (1977$) of energy storage automobiles designed to maximize the use of electricity.

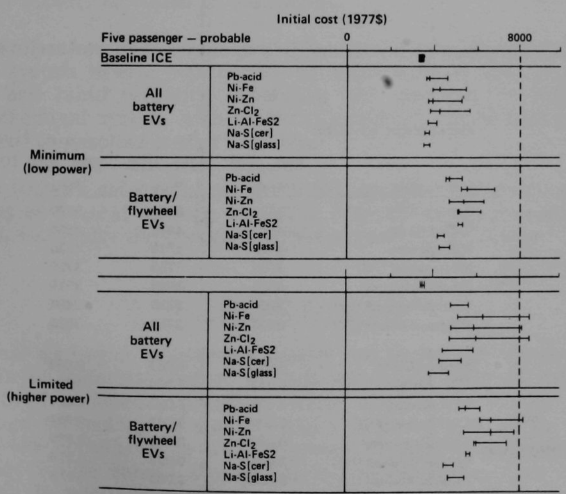


Fig. 2. Projected effect on initial cost of adding a flywheel to EVs.

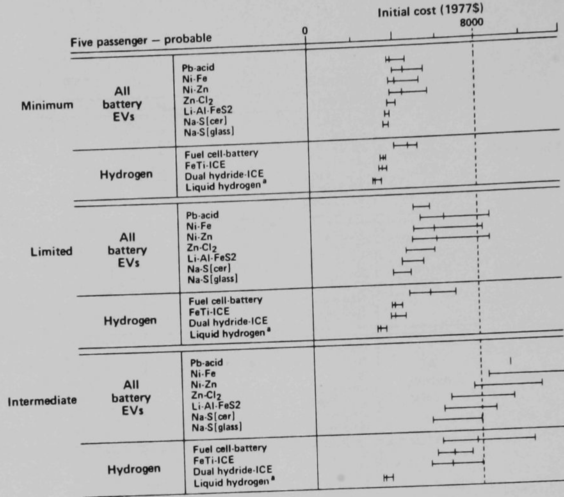


Fig. 3. Comparison of the initial costs (1977$) of hydrogen and electricity powered automobiles

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a Microsphere-ICE automobiles were not projected available at the probable level.

Table 5. Comparison of initial and life cycle costs of power-leveling hybrids.

Five passenger — probable

	Vehicle type	1980 - 1985 Prob	1985 - 1990 Prob	1990 - 2000 Prob
Initial user cost (1977$)	Baseline ICEV	3490	3550	3620
	ICE/comp air	4540	4400	4360
	ICE/hyd accu	4400	4370	4330
	ICE/flywheel (FC)	3780	3750	3720
	ICE/NiZn battery	4070	3830	3710
	Turbine/flywheel (Iso)	3960	3830	3650
	Turbine/flywheel (FC)	3910	3750	3620
Life cycle cost (1977$/km)	Baseline ICEV	0.085	0.086	0.088
	ICE/comp air	0.097	0.095	0.094
	ICE/hyd accu	0.098	0.097	0.097
	ICE/flywheel (FC)	0.087	0.087	0.087
	ICE/NiZn battery	0.099	0.090	0.086
	Turbine/flywheel (Iso)	0.085	0.079	0.076
	Turbine/flywheel (FC)	0.084	0.080	0.075

- Near-term EVs are expected to achieve only minimum and limited performance.

- Most ESVs will weigh more and cost more than their ICE equivalents. This cost differential will decrease with time.

- If ESV performance is reduced, then these automobiles can be more cost-competitive with today's ICE vehicles.

- The Pb/acid battery system is projected as having the lowest cost for minimum-performance EVs and for the dual-fueled hybrid vehicle (DFHV) in the near term at the equivalent-performance level. In later time periods, the advanced batteries allow better performance and also have lower initial and life cycle costs for EVs at the minimum and limited-performance levels.

- Flywheels or other mechanical-energy storage devices appear advantageous in higher performance EVs, where the cost of the battery capacity needed to reach a required acceleration level may be much greater than the cost of achieving this capability using a mechanical power boost system.

- Hydrogen systems compare favorably in cost with the all-battery EVs. Liquid-hydrogen storage systems approach the ICE systems in initial cost at the equivalent-performance level but have higher life-cycle costs in the early time periods.

- Dual-fueled hybrids are projected to provide vehicles of equivalent performance over all time periods, at costs comparable to the limited-performance EV. However, petroleum costs and availability could seriously affect the status of the DFHV.

- Although performance and cost projections for the exploratory Al-air battery system have a high degree of uncertainty at this time, the specific energy and rapid refueling capability are expected to make it the only electrochemical system with realistic prospects for achieving performance equivalent to gasoline-fueled vehicles.

- Factors such as safety, supply problems, and infrastructure impose serious problems on several systems including thermal-energy storage and hydrogen systems, especially the cryogenic liquid system.

CURRENT ANALYSIS

This year we began to examine market and technology development trends, and to obtain an understanding of what is and is not believed important and/or what is believed technically possible. While emphasis is on the application of energy storage technology to electric and hybrid vehicles, other transportation applications are considered as well. Current transportation developments and trends impact future energy storage device requirements. We are monitoring these trends. In addition, technological developments which improve storage device characteristics or provide greater confidence that desired goals will be reached change the projected role of those devices in transportation. Our efforts then are directed toward determining the impact of these developments on electric and hybrid vehicle technology and commercialization, as well as other transportation applications. Analysis efforts are also being monitored to identify market and technology trends that may be implied by them. In addition, where incorrect data has been used or data has been incorrectly used to provide market and technological projections, the errors in such projections and the source of those errors are being identified in order to clarify misunderstandings.

We have investigated many claims of device improvements. No major advances have been substantiated which are not known to the energy storage community. We also have not yet uncovered any significant market trends in this country which will effect R&D on energy storage devices.

For examining the procedures used and thus the validity of the results in current EHV and energy storage device analyses, we have developed a rigorous evaluation approach. This approach involves a generalized procedure for assessing energy storage systems. The procedure consists of several steps. When we review a report, we ask at each step if the data used to arrive at that step was correct and if the method used to generate the required outcome using that data was correct. We report results to DOE/ACT using the general format. The information base used for the comparison is that which has evolved from the ESS study. However, that study made projections on "best" available data. New information, either improving data or evaluation methods, is being studied to understand its influence on the projections. But first, the validity of such data is questioned.

To date, numerous studies have been reviewed to determine if their vehicle performance predictions, as well as transportation system implications, were arrived at using correct energy storage device data and whether consistent analytical methodologies were used. In general, the analysis methods were relatively consistent, although there were projected battery characteristics used that were different from our former study. Specifically, we have thus far found the following:

- In some cases the peak power requirements of a vehicle and thus of the energy storage device were not considered. In some vehicle applications, they can be more demanding than energy requirements.

- In some analyses comparing various energy storage devices for use in vehicles, we found that systems were not compared on a consistent basis. For example vehicles were compared for energy efficiency when the vehicles had different range capabilities. Normalizing for range gives quite different results.

In order to insure that our database is as current as possible and that currently reported technology data is correct or is reported in a manner that allows correct interpretation, we are reviewing performance data from some 68 E and HV manufacturing firms, as well as replies from an additional 23 E and HV and/or energy storage system companies. In addition, we have contacted an additional 50 of these firms and expect replies in the near future. This information is being analyzed and, as mentioned, is becoming an important part of our current information base. We plan to retain this information in a form that can be readily reviewed and updated to assist us in making performance predictions and determinations of the impact on energy storage systems development. We also plan to make this information available on the Technology Information System (TIS).

This study was just initiated this fiscal year and, therefore, it is too early to draw definite conclusions. However, there are a few important factors that are surfacing because of it. They include:

1. Many analyses of systems overlook subtle factors which can totally change the results.

2. There should be better representations of batteries as power sources. Such a representation must include factors such as peak power demand, cycle life as a function of depth of discharge and rate of charge, to mention a few.

3. Analyses often do not consider attributes which influence acceptability. For example, more emphasis should be placed on safety and environmental factors, particularly for the more volatile sources.

4. This study is also pointing out the need for an up-to-date database and the reduction of information to a common basis.

REFERENCES

1. J. G. Bolger, et. al., Application of Energy Storage Power Systems to Nonhighway Transportation, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52333 (1977).

2. L. G. O'Connell, et., al., Energy Storage Systems for Automobile Propulsion: Final Report, Lawrence Livermore National Laboratory, Livermore, CA., UCRL-53053-80, Vols. 1, 2, 3 & 4 (1980).

ALUMINUM-AIR BATTERY SYSTEM
ASSESSMENT OF TECHNICAL AND MARKET VIABILITY
FOR ELECTRIC VEHICLE APPLICATION

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ABSTRACT

This project was an assessment of the viability of the aluminum-air battery, with mechanically replaceable anodes, as a power source for electric vehicles. The system is a high energy density system, in the range of 200-400 w.h./kg depending on size, and other parameters, and offers the possibility of extended range vehicles. Technical and market problem areas were analyzed and suggestions listed for continuing research priorities. The cost and infrastructure for replacing and reforming the aluminum electrode is the major component in the cost projections for the system. Studies have not yet progressed to the large multicell battery development stage so the mechanical and cost aspects of the system are projections with considerable variability at this point.

ASSESSMENT AND EVALUATION SCOPE

This project was an assessment of the technical and market viability of the aluminum-air battery as a power source for electric vehicles. However, this assessment was carried out while the system is still in the comparatively early research stage. The calculations and conclusions are based on reported laboratory findings which are still variable and improving. The recommendations and conclusions are therefore best used as a guide to identifying problem areas and as a help to establishing priorities for research and development. As the chemistry and mechanics of the system become fixed, and a degree of manufacturing variability established, a more exact assessment of the role of this battery system in the electric vehicle program will be possible.

TECHNICAL BACKGROUND

Aluminum and other metals more negative than zinc are fundamentally incapable of being recharged or reformed from aqueous electrolytes. Various battery systems using high energy anodes have addressed this situation by utilizing non-aqueous organic electrolytes, or molten salt electrolytes (at elevated temperatures). Another approach, as used in the aluminum-air battery, is to mechanically replace exhausted electrodes with new electrodes and to reform the aluminum external to the battery in standard, non-aqueous molten salt cells of the aluminum industry. This concept brings into consideration an infrastructure different from that of the normal battery user. The concept has, on the surface, some extreme virtues. It would shift the energy base for recharge from electrical energy, which is used in plug-in battery chargers, to the general energy base of the aluminum industry with the opportunity to use hydro-electric and coal power for the aluminum production cells. However, at the moment, the infrastructure for mechanical replacement of electrodes and collection and shipping of discharged battery material is not in place and possible problem areas are discussed in the report.

TECHNICAL ASSESSMENT

The aluminum-air battery appears to be capable of being a very high energy density power source in the order of 200-300 watt. hrs. per kilogram with volumetric energy densities in the range of 120-200 watt. hrs. per cubic decimeter. This is shown in Figure 1 as a function of the probable power requirements for different sized vehicles. There are two major parameters that affect the energy density of this battery system. One is the power required for each size; the other is the ratio of aluminum to water carried aboard the vehicle. For this calculation we have used a 35 kilowatt hour battery at a 30-kilowatt rate for the calculation of the small vehicle performance, 80-kilowatt hour battery at 50-kilowatt rate for an intermediate, and 200-kilowatt battery at a 70-kilowatt rate for a van or large vehicle. The plot shows energy densities at two ratios of aluminum to water. The concept proposed by the Lawrence Livermore research group is shown as the n=4 curve. That is, four times the aluminum capacity is carried on board as the amount of water needed to react with it. This means the aluminum would only have to be replaced one-fourth as frequently as water. Higher energy densities would be obtained when equal reacting masses of aluminum and water are carried aboard the vehicle, shown as the n=1 curve. In any case, the aluminum-air battery appears to be capable of being a very high energy density system based on extrapolations of current single-cell experiments. The major technical strengths and weaknesses of the system are summarized in the following table:

Technical Strengths and Weaknesses

Strenths

- High energy density cell system
- Compact - high volume density
- Moderate temperature operation

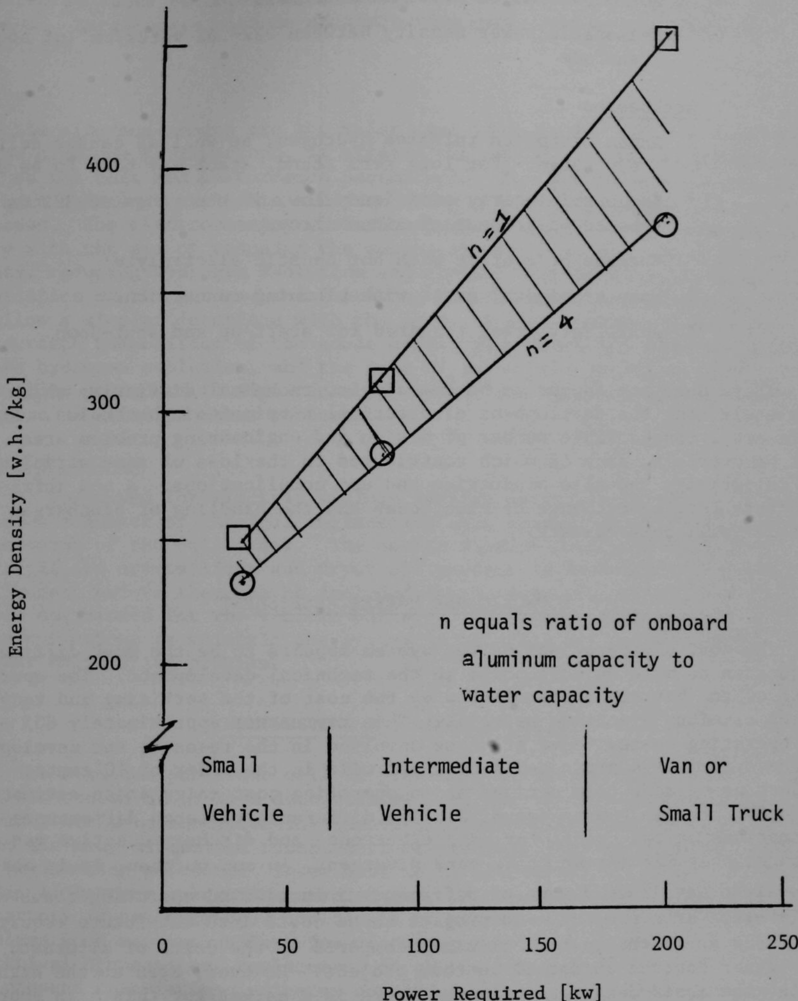

FIGURE 1 - Energy Density Calculation of Aluminum-Air Batteries as a Function of Size.

Assumptions:

	Battery Size	Power Required
Small Vehicle	35 kwh	30 kw
Intermediate Vehicle	80	50
Large Vehicle	200	70

- Not dependent on critical materials
- Reasonable power density between .22-.62 watts/cm^2 of anode surface

Weaknesses

- Anode corrosion releases hydrogen, as well as causes self-discharge. For long term stand, stack may have to be drained.
- Round-trip energy efficiency low, in the range of 32% to 43%, based on present aluminum alloys.
- Hazards of contact with hot caustic electrolyte
- Many mechanical parts with plumbing connections
- Auxilliary power required for start-up and shut-down

There does not appear to be one single, technical difficulty which would completely stop the development of practical aluminum-air batteries. Rather, there are a considerable number of design and engineering problem areas which must be overcome, each of which contributes to the loss of some efficiency and reliability and also production and use complications. A new infrastructure for the exchange of electrodes and the handling of discharged material will be necessary.

ECONOMIC AND MARKET ASSESSMENT

The cost of operations of the system appears to be the most difficult projection to make at this point in the technical development. The operating costs of the battery are dominated by the cost of the servicing and recycling of the aluminum electrode material. This represents approximately 80% of the operating costs. Some of those involved in the research and development of the system have projected a cost per mile in the order of 10 cents. This project assessment team arrived at an operating cost calculation estimate in the order of 16-17 cents per mile. The difference reflects differences in assumptions on the credit for used electrodes and discharged active material. Although they may appear to be very divergent, in our opinion, it is not unusual to have this degree of difference in projected operating costs at this early stage of a project. To project these costs into the future requires a judgement as to the cost of aluminum compared to the costs of alternate fuels and is not covered in detail in this project. However, even at the higher costs, the assessment team believes there is a market for this high energy density power source in some particular niches of the electric vehicle and fork lift truck industry.

COMPONENT ANALYSIS

Air Electrode

The air electrode appears to be performing reasonably well in small size continuous operation. Data is needed in determining the effect of size on variability, including wetting, and of the changing drain rate, intermittent operation, and extended lay-up. The useful life characteristics may also be affected by these factors, particularly in the presence of stannite and gallium. Large-scale cathode manufacturing processes have not yet been identified.

Anodes

The aluminum anodes are the major cost item of the cell. The corrosion of the aluminum is important; it affects the use and market acceptance as well as the cost and performance parameters. The initial work on the battery has been done with available aluminum alloy electrodes designed for other purposes. The electrochemistry of the aluminum should be investigated more fully with the aim of reducing the amount of expensive and strategic alloying agents, reducing hydrogen evolution and controlling the self-discharge characteristics of the system, and improving the voltage current density response to allow a simpler interface with the load. A more thorough understanding of the surface composition of the anode during discharge, the kinetic mechanism of the hydrogen evolution, and the role of impurities on these kinetics might well allow designers to significantly improve the aluminum-air cells for electric vehicles or other purposes.

Other Components

As conceived for electric vehicle applications, the aluminum-air system includes a number of chemical engineering unit operations which support the functioning of the cell stack. The carbon dioxide absorber, humidifier, hydrargillite crystallizer and dryer all present interesting engineering challenges, before they can be included in the compact, maintenance-free system envisioned for the vehicle battery. The integration and control of these operations to maintain the system in material and heat balance is a further engineering problem.

CONCLUSIONS AND RECOMMENDATIONS

1. The aluminum alloy-air cell is presently in the research stage. Small single research cells have demonstrated very high energy and volume densities and many design and engineering innovations have been achieved. However, there are many unresolved fundamental electrochemical, manufacturing, design and engineering problems. These have to be investigated, scaled up, and multicell battery operations carried out, before technical feasibility as an EV battery is demonstrated. Multicell operation usually generates other problems such as, non-uniform temperatures, intercell parasitic currents, electrical connections, replacement of parts, and non-uniformity of components. The present calculation indicates operating costs to the user of approximately 16-17¢ per mile at today's aluminum prices.

There are other approaches to the goal of long-range electric vehicles, which appear to be more rapidly realizable and, in addition, may be more energy efficient. The ICE storage battery hybrid would have a simpler infrastructure and would almost fit within the present infrastructure.

2. The assessment team believes that there are special applications for this innovative technology, aluminum-air system. Some of these are in special electric vehicles and material handling trucks where the economics of this system, even from a pessimistic view, would be acceptable.

3. The likely market niche for this system is in fleet vehicles, or other large groupings of vehicles, where a service facility can be integrated into the infrastructure. The projected cost per unit of the system makes it most attractive as a replacement for inefficient stop-start vehicles such as delivery vans, service fleets, utility equipment and buses.

4. Recommendations

a) The aluminum alloy-air cell should be investigated in a fundamental way because it is capable of providing a high energy, density convenient, energy source for some special applications.

b) Multicell studies (5 cell minimum) should be carried out in the 25 cm by 40 cm proposed electrode size to identify multicell problems, as soon as possible.

c) Sufficient cells should be built of one size and chemistry to identify cell-to-cell variations and variability of the components. These groups should be run through simulated cycles to study performance and problems of intermittent use, extended storage, and safety.

d) A most important factor to be investigated near term is the mechanical replacement of the anodes. This must be demonstrated to be quick, efficient, mechanically simple, safe, and leak proof. A considerable cost variation estimation exists because this has not yet been done.

e) There exist other possibilities of making a power cell, not using an aluminum sheet; for instance, aluminum balls in a noncorroding anode basket. These could offer considerable operating economics and should be considered.

f) Increasing the energy efficiency of the system by a fundamental study of the aluminum alloy has a major economic benefit.

COMMENTS ON TECHNOLOGY ASSESSMENT

The assessment team appreciates the cooperation of the staff of Lawrence Livermore National Laboratory and others in providing material and discussions of the interpretation of present data and concepts. This assessment is, as are others, done on a one-time basis; it is a snap-shot of a moving story and can best be used to identify problem areas and decision points. We believe an ongoing evaluation is necessary of major projects of this type and recommend a program advisory board including members outside of the project team and the industry associated with it. This board should have knowledge of the economic and technical characteristics of other systems and have manufacturing experience, so that realistic and credible comparisons and projections are feasible. The board should review the economics and human safety engineering, manufacturing process, investment, and return investment calculations on a continuing and/or regular basis. It would also be possible to analyze other approaches to the goal of electric vehicles, especially long-range vehicles, and to compare their time-table for development, energy efficiency and market acceptance factors.

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COST-EFFECTIVE GOALS FOR BATTERY RESEARCH

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ABSTRACT

During 1980, a methodology was developed for identifying battery R&D goals which are optimum for electric vehicle missions. This paper describes the general outline of this methodology and shows some typical results for the case of lead-acid batteries used in "second cars". The 1977 National Personal Transportation Study provided the basis for establishing range and payload requirements.

I. INTRODUCTION

The objective of this work is to develop a logical, understandable, and valid method for establishing battery R&D goals which are optimum for electric vehicle applications. The method has the following features: (a) comprehensive modeling of key battery relationships, (b) avoidance of premature specification of battery or vehicle characteristics, (c) identification of range, acceleration and payload which match EV mission requirements, and (d) optimization using the minimum-ownership-cost criterion.

Argonne National Laboratory, Energy & Environmental Systems Division, began this effort in June, 1980. During 1980, a closed-form mathematical system was established and sample computations (involving sodium-sulfur batteries in fleet light trucks and fleet autos) were made to illustrate the technique. Total discounted user cost-per-km was selected as the objective parameter to be minimized. The combination of

*Consultants

characteristics which led to least cost represent potential research goals for the battery developer.

In 1981, work is progressing toward the derivation of battery goals based on careful statistical analysis of the 1977 National Personal Transportation Study data for 2-car households. Preliminary results have been obtained for lead-acid and nickel-iron battery powered vehicles for the "second car" mission. Highlights of the FY-81 work include: (a) analysis of cycle life/depth-of-discharge effects, and (b) development of an equation which depicts the interrelationship between specific energy, peak power, and cost.

II. METHODOLOGY

The goal derivation methodology rests on the analytical characterization of four key elements. These are:

1. Electric Vehicle Technical Description,
2. Battery Technical Description,
3. Vehicle and Battery Costs, and
4. Mission (Usage) Description.

Total discounted user costs per unit distance are computed based on these four elements and minimized over appropriate data input ranges. The resulting battery characteristics at the minimum cost are the goals for the particular case studied.

Data bases and functional relationships have been developed for sodium-sulfur (ceramic electrolyte), lead-acid, and nickel-iron batteries. Vehicle data have been collected for two-car households, fleet light trucks, and fleet autos. Additional battery and vehicle types will be studied in future work.

A. Battery Technical Characterization

Battery research and development programs have many possible areas of technical emphasis. Among these are:

- Specific Energy
- Peak Power
- Cost
- Cycle Life
- Volumetric Energy
- Sustained Power
- Ruggedness
- Maintenance Frequency
- Ability to Withstand Environmental Stresses

However, funding limitations prevent an "all-out" assault on each of these battery performance factors. Years of research are generally required for major advances, and in any case there are interactions among these parameters which tend to compromise other factors when one is improved. Clearly, battery goals and research priorities must be carefully selected so that maximum technological improvement can be achieved with the relatively scarce research and development resources that are available. Specific energy, peak power, cost, and cycle life are generally regarded as being the most critical battery factors, and the battery goal derivation method concentrates on these four. In this analysis, battery energy, power, and cost are functionally interrelated as shown in Fig. 1.

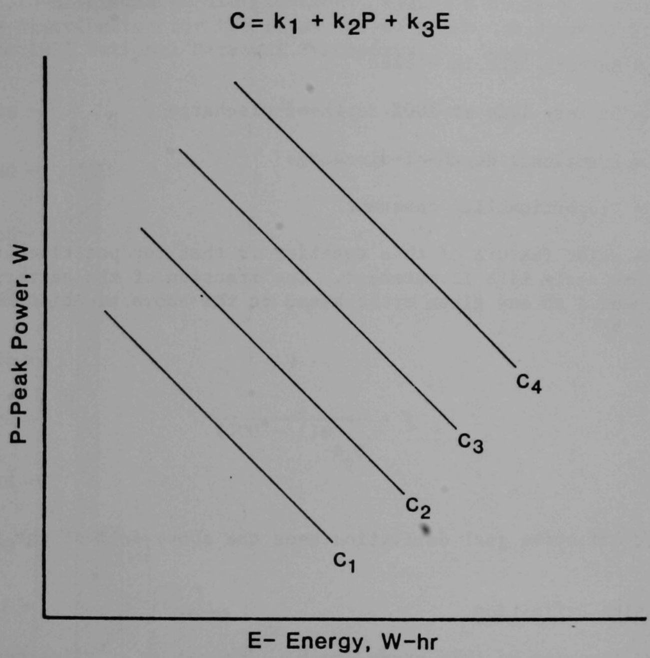

Fig. 1 Cost -- Power -- Energy Relationships

Increasing on-board energy and power are directly associated with increased battery costs. This relationship is supported by the work of Nelson[1] and Symons[2] who present coefficient values for various battery systems.

Battery cycle life is influenced, in many systems, by the fraction of capacity removed on any given cycle (depth-of-discharge). However, there is little available data to describe this relationship for the majority of battery systems under consideration. Seiger[3] has summarized recent information in this area and suggests the use of the following relationship for lead-acid, nickel-iron, and nickel-zinc.

$$L = L_o e^{\alpha(1 - DOD)} \tag{1}$$

where:

L = Battery life in cycles

L_o = Battery life at 100% depth-of-discharge

DOD = Fractional depth-of-discharge

α = Proportionality constant

The major feature of this equation is that for positive values of α, battery cycle life is extended. The fraction of the battery's cycle life expended on any given cycle based on the above equation can be shown to be:

$$f = \frac{1}{L_o e^{\alpha(1 - DOD)}} \tag{2}$$

The cost-effective goal derivation uses the above form of the relationship.

B. Mission Definition

For purposes of this study, we have relied on existing computer models for both data and formulation techniques. Specifically, the EXXON[4] and LLL[5] models have provided several key inputs. Also, the work of Hamilton[6] gives valuable insight into the problems associated with defining future vehicle usage patterns.

Several vehicle parameters must be assumed prior to this analysis. For example, a vehicle energy consumption of 0.102 Whr/kg·km has been adopted from the EXXON study as being fairly representative of an advanced electric vehicle. Also, the vehicle power-to-weight ratio (acceleration requirement) was assumed to be 27 W/kg -- a number defined by the standard acceleration required for the SAEJ227aD driving cycle. However, these and other vehicle assumptions can be adjusted to suit the methodology user's assessment of the future capabilities of vehicles.

Sample calculations have been carried out for vehicle ranges corresponding to 25, 50, and 75% potential market fractions. However, the user can input whatever values he feels are proper. The ranges can be specified by use of daily mileage distributions, or single point design ranges. In this analysis, the range represents the minimum daily distance which will fully satisfy the mission requirements. The daily mileage trip distribution is an important input for battery systems (such as lead-acid) in which cycle life is a strong function of the battery depth-of-discharge distribution. Figure 2 shows a typical daily mileage distribution for the first car of a two car household obtained from the 1977 National Personal Transportation Study.[7]

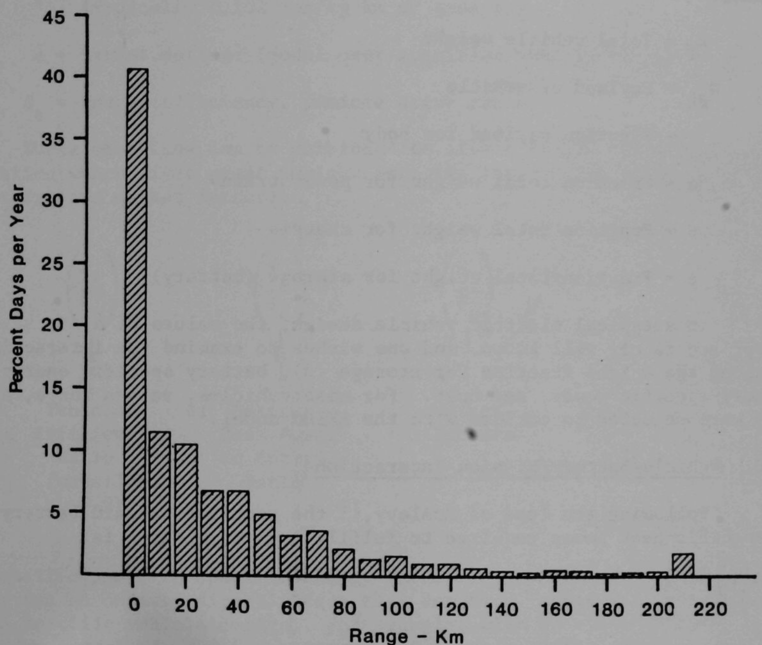

Fig. 2 First Car Daily Distance Traveled

Maximum vehicle payload is also specified by the model user prior to the analysis. Generally, we have assumed half of the payload onboard, but this fraction can be varied as the model user desires.

C. Vehicle Design

An important factor which needs to be modeled is the vehicle weight. In this work, a variant of the equation prepared by McAlevy[8] and Nelson[9] is used:

$$W_T = \frac{W_{PL}\ (1/2 + \gamma)}{1 - \alpha - \beta - \delta} \tag{3}$$

where:

W_T = Total vehicle weight

W_{PL} = Payload of vehicle

γ = Fraction payload for body

α = Fraction total weight for power train

β = Fraction total weight for chassis

δ = Fraction total weight for storage (battery)

In a typical electric vehicle design, the values of α, β, γ, and W_{PL} are fairly well known, and one wishes to examine the interaction among the weight fraction for storage (δ), battery specific energy, battery specific power, and cost. For most vehicles, values for α, β, and γ were selected to conform with the EXXON model.[10]

D. Vehicle/Battery/Mission Interaction

Following the lead of McAlevy,[11] the required onboard battery specific peak power required to fulfill a given mission is:

$$S_p = \frac{P_v}{\delta_v \cdot P_\varepsilon} \tag{4}$$

where:

P_v = Market defined (model user specified) vehicle power-to-weight ratio (typically 27 W/kg or greater)

P_ε = Power efficiency, vehicle drive train

δ_v = Weight fraction onboard battery storage

Likewise, the required onboard specific energy required to fulfill a given mission is:

$$S_E = \frac{E_v \cdot R}{\delta_v \cdot E_\varepsilon} \tag{5}$$

where:

E_v = Energy consumption per-unit-weight, per-unit-distance (typically 0.102 Whr/kg·km or greater)

R = Market defined (model user specified vehicle range)

E_ε = Energy efficiency, vehicle drive train

These equations can be combined* to give a single dimensionless equation which gives great insight into the interaction among vehicle, battery, and market factors:

$$\left(\frac{P_\varepsilon}{E_\varepsilon}\right) \cdot \left(\frac{S_p}{S_e}\right) \cdot \left(\frac{E_v}{P_v}\right) \cdot R = 1 \tag{6}$$

Vehicle Efficiency Ratio (usually ∿0.9)

Battery Peak Power to Energy Ratio

Market Factors

A specific power to specific energy ratio for an electric vehicle battery can be derived directly from this equation, often without reference to a specific vehicle design. For example, with E_V = 0.1 Wh/kgkm, P_V = 27 W/kg, and $P_\varepsilon/E_\varepsilon$ = 0.9 a battery peak power/specific ratio of 3.0 is required for a range of 100 km. At 200 km vehicle range, this ratio drops to 1.5 -- an entirely different storage system from the battery designer's standpoint. Careful identification of market requirements is needed in order to define goals which appropriately direct electric vehicle battery developers' efforts.

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*By elimination of the common factor, δ_v.

III. SAMPLE CALCULATION

The interesting case of lead-acid batteries used in electric vehicles targeted for the two-car household has been examined. A daily mileage distribution similar to that shown in Fig. 2 was assumed to be typical for this segment of the market. Based on this distribution, vehicle ranges of 80, 100, and 125 km were judged to represent 25, 50, and 75% market usage fractions. An electric vehicle design with specific energy consumption of 0.102 Wh/kgkm and a power-to-weight ratio of 27 W/kg was specified. The weight fraction of batteries in the vehicle was arbitrarily chosen to be 0.3 in this example.

The battery specification included α and L_o coefficients that are appropriate for a battery capable of 800 cycles at 80% depth of discharge (α = 2.0 and L_o = 540). The battery cost equation coefficients in this sample calculation were:

$$k_1 = \$871 \qquad k_2 = \$0.0107/W \qquad k_3 = \$0.0282/kWh \tag{7}$$

as suggested by Symons.[12] The battery characteristics (minimum total user cost) resulting from this particular set of assumptions are:

Battery design DOD - 60-80% @ minimum total user costs

Battery life - 10-12 years (2200-2400 cycles)

Battery cost - $2200-2400

Specific energy - 63-72 Wh/kg

Specific peak power - 112 W/kg

Total user cost - 10-14 %/km

(The lower numbers shown are associated with the 80 km vehicle range assumption -- the higher number with 125 km.)

All the characteristics shown are reasonable targets for lead-acid batteries in 1985 with the exception of battery specific energy which is too high. Examination of the input data indicates that the specific energy requirement can be reduced by an increase in battery weight fraction or, in a more informative way, by adjustment of α and L_o in the battery life equation. If the battery cycle life is made less sensitive to depth-of-discharge (DOD) with α and L_o values of 0.5 and 725, respectively (these numbers maintain the 800 cycle life at 80% DOD), then the optimum DOD becomes nearly 100% and the specific energy requirement drops to 38-60 Wh/kg -- which is more reasonable. This necessary reduction in required specific energy results in an increase in operating costs of ∿3¢/km, however. From this example, it clear that the individual battery characteristics must be constrained within reasonable limits to avoid derivation of impossible battery goals.

The lead-acid battery goals resulting from this revised analysis are given below:

Maximum DOD - 99%

Battery life - 10-12 years (2200-2400 cycles)

Battery cost - $2200-2400

Specific energy - 38-60 Wh/kg

Specific peak power - 112 W/kg

Total user cost - 13-17¢/km

IV. FUTURE WORK

Present work is focusing on determining the sensitivity of total user cost to changes in the individual battery and vehicle parameters. A research priority ranking can be obtained for each battery characteristic by multiplying this sensitivity factor by the percent improvement expected to result from an intensive research effort. An attempt will be made to develop an advanced goal-setting methodology based on this sensitivity analysis.

REFERENCES

1. Nelson, P. A. ,Argonne National Laboratory, unpublished information, Aug., 1980.

2. Symons, P. C., Detroit, March, 1981.

3. Seiger, H. N., "Effect of Depth of Discharge on Cycle Life of Near-Term Batteries," Proc. Intersociety Energy Conversion Engineering Conf., Atlanta, Aug., 1981.

4. Gaines, L. H., Nazimek, K., "Development of Evaluation Techniques for Electrochemical Energy Storage Systems", Final Report Contract EM-78-C-01-5157, EXXON Research & Engineering Company, Linden, N.J., March 15, 1980.

5. Behrin, E., <u>et al.</u>, "Energy Storage Systems for Automobile Propulsion, UCRL-52841 (Volume 2)", Lawrence Livermore Laboratory, University of California, Livermore, CA, December 15, 1979.

REFERENCES (Cont'd.)

6. Hamilton, W., "Effect of Battery Performance and Cost on Market Share of Electric Cars", General Research Corporation, Santa Barbara, CA, March 1980.

7. 1977 National Personal Transportation Study public use computer data tapes, Federal Highway Administration.

8. McAlevy, R. F., "Energy Storage in Automotive Vehicles, An Analytical Model", Invited Presentation for International Assembly on Energy Storage, Dubrovnik, Yugoslavia, May 27-June 1, 1979.

9. Nelson, op cit.

10. Gaines, op cit.

11. McAlevy, op cit.

12. Symons, op cit.

CHAIRMAN'S SUMMARY OF PANEL DISCUSSION

SESSION IV
STORAGE FOR TRANSPORTATION

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The Chairman, Robert McAlevy, opened the Session by posing three related questions: "Would differences between the various results and projections presented during this Session (and, in fact, during the entire Conference) lie within the same error-band if the uncertainty in the calculated outputs were made to reflect fairly the uncertainty in knowledge of the assumed inputs? Specifically, would this be the case for the aluminum-air battery vehicle, where Lawrence Livermore National Laboratory projected a vehicle cost of \$0.11/mi, and Professor Salkind projected \$0.16/mi? Unless "error analyses" are incorporated as an integral part of the work, how is it possible to discern real differences from apparent differences in the subject results, projections, etc.? (The Chairman noted he did not request a direct answer from members of the panel or the audience but suggested that many potential questions from the audience might be answered if error analyses had been included in the work presented at the conference.)

Comment from V. Hampel, Lawrence Livermore National Laboratory:

The computer generates output to nine significant figures. It is correct that their uncertainty should be indicated. But this information can be listed somehwere else in the report and not necessarily included as an integral part of the reported results.

Comment from R. Elliott, Argonne National Laboratory:

It is of the greatest importance to focus on the input numbers and their uncertainty and to debate their values in open forums such as this. It is equivalent to "peer review".

Question for A. Salkind, Salkind Associates:

What kind of improvement might come out of using different aluminum alloys?

Response by A. Salkind:

The chance of getting part of the difference back between 1.6^{v} and 2.8^{v} (an enormous loss of energy), and a chance of reducing the evolution of H_2.

The alloy being used by USA groups was designed for use in a sea water torpedo bouy, not for EV applications.

Question for L. O'Connell, Lawrence Livermore National Laboratory:

In contrast to the vast experience with batteries in a variety of applications, there appears to be little experience with flywheels for transportation applications. Where do you get your input values used in projecting flywheel vehicle technical and economic performance values?

Response by L. O'Connell:

Many flywheel developers believe that the figures used in the LLNL flywheel work were too pessimistic!

Question for R. Elliott, Argonne National Laboratory:

Did you consider impact of both cars being in use at the same time when you modeled the two-car family market for EV's?

Response by Elliott:

Yes. The EV takes the shorter range trip.

Question for R. Elliott, ANL

If you employed smaller and cheaper batteries and wore them out sooner, and, therefore, replaced them sooner, my calculations show that you get a lower EV life-cycle cost than for the case of larger, more expensive batteries with a correspondingly greater lifetime. This might result from the need to discount the future cost of replacement batteries.

Response by Elliott:

As has been said here previously, the results obtained from all such calculations are extremely sensitive to the input values assumed, particularly the assumed values of cost coefficients and trip distributions. Our differences in assumed values could well result in our different outputs.

Comment by A. Salkind, Salkind Associates:

The number of useful cycles obtained from a battery is easily as sensitive to the method of charge and charge control as depth of discharge. What voltage are you controlling charge at? Are you cutting off at a certain specific gravity for a lead-acid battery? Also, it is important to know if the battery is allowed to cool down (after discharging to a certain point) before charging, so that it is not destroyed by heat buildup.

Comment by R. Elliott, ANL

In our calculations, a well-characterized, temperature-corrected charging characteristic was assumed.

Question for R. Elliott, ANL:

Did you account for the recycling of batteries in your calculation of EV cost?

Response by Elliott:

Yes, in every case, although the uncertainty in such values are necessarily high.

Comment by K. Hoffman, Mathtech

Results presented at this Conference stem from analyses funded by the Federal government as an aide to their EV commercialization activities. Are they also useful to the private sector in their EV commercialization activities?

Response by L. O'Connell, Lawrence Livermore Laboratory:

The industry does make use of transportation studies such as were presented here.

Comment directed to L. O'Connell:

Your projected values for H_2 vehicles are more attractive than those for EV's. What inhibits a push for H_2 systems over battery systems?

Response by L. O'Connell:

The unavailability of large H_2 supply at economic costs. However, should the demand for EV's increase dramatically over the next few years, say as a result of another cutoff of imported petroleum, it is unlikely that battery manufacturers will have the production capacity in place to meet such strong demand. Perhaps there is a rate for the Government in insuring the existance of an adequate supply of EV batteries.

Comment by A. Salkind, Salkind Associates:

Presently, the lead-acid battery industry is operating at only 60% of capacity on a one-shift basis. Presently, 63 million 12^v units are being produced annually.

Comment by F. Salzano, Brookhaven National Laboratory:

The present Administration has indicated a willingness to fund longer-range research projects. Can the output of any of the work we heard about here be used in the definition of long-term cost-performance goals for EV batteries? If so, then that information should be made available to the people who will do the long-range research in this area, so they will have well-defined objectives for their work.

Response by R. Elliott, Argonne National Laboratory:

We feel our methodology is very useful in doing what you ask for, and we will be reporting further results in detail in the near future.

Comment by A. Salkind, Salkind Associates:

In analyzing any system in a useful and valid way, it is necessary to identify the value judgements made and basis for selecting the values chosen. These values must be updated on an ongoing basis as the cost of energy and battery components change.

The chairman summarized by noting that many of the questions raised dealt with the choice of values for input parameters used in the various analyses presented here. All participants who offered an opinion on the issue agreed that the choice is key, since the values used as "input" determine uniquely the values of "output" parameters produced. If those making the analyses would produce a list of input parameters and the uncertainty assigned to each, it would be easier to rationalize differences in the output for such analyses.

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